Measuring Travel Behavior and Transit Trip Generation Characteristics of Transit-Oriented Developments

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ABSTRACT

Transit Orientated Developments (TODs) have been recognized as a promising proposition for policy makers and land developers to meet the challenges of urban sprawl. The rapid pace with which TODs are being developed across United States has left policy makers and transportation planners looking for methods aimed at modeling travel characteristics of TODs. Current ITE trip generation models are generally based on consolidated survey data from various landuses and are inadequate in serving the planning needs for travel demand parameters necessary to predict trip generation rates, develop trip distribution tables, identify mode choice characteristics, and determine trip assignment of TODs.

The primary foci of this research are to understand the trip making behavior of the TODs and develop a methodology for determining vehicular trip generation rates. Comparative assessment of TOD vis-à-vis non-TODs with respect to trip rates, transit usage, and primary travel mode is performed. A regression model relating TOD trip ends to gross floor area (GFA) is developed and validated. Model behavior is consistent with the industry state-of-practice which will assist transportation practitioners accurately forecast trip generation rate for TODs. Validation of the regression model is performed by checking for normality, multicollinearity and heteroscedasticity of the independent variable.

The activity-based survey data used for this research is associated with the Washington D.C. Metropolitan area which 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.
INTRODUCTION

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 and livability are now the focal points in planning for transportation improvements.

In the context of urban planning, the concept of smart growth - which promotes higher density, mixed use developments concentrated along transit corridors - is a robust alternative to the status quo. At the core of smart growth strategies resides Transit-Oriented Developments (TOD). TODs are a form of land use that attempts to reduce the amount of travel by car by providing a walkable access to a transit facility. Due to the novelty of this type of land use, 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.

The exact definition of transit oriented developments and the criteria used to correctly classify a TOD development is scattered throughout the literature. For the purposes of this research several parameters were used to select an appropriate transit-oriented corridor. These parameters are the common denominator of all definitions of transit-oriented developments 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 served by transit. The transit technology includes heavy or light metrorail, streetcar, 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 an integral parameter associated with TODs.

4. Pedestrian and bicycle friendly – A well connected pedestrian and bicycle facility is an essential component in classification of a land use as a TOD.

Accurate trip generation models are essential in the traditional four-step travel demand model and in the planning process for transit-oriented developments. It ensures accuracy when
determining impact fees as well as the magnitude of transportation improvements required by the
development. Over-estimation of trip generation rates is disadvantageous to private sector
developers because it would result in higher impact fees. It discourages developers to fully
pursue TODs as a viable land use that offers higher density and lower impact fees. Similarly
under-estimation of trip generation rates would result in insufficient roadway improvements,
adverse for local or state governments.

The primary objectives of this research are to explore trip-making characteristics of
transit oriented developments and, secondly, determine their trip generation rates. Comparative
assessment of TOD areas vis-à-vis non-TODs with respect to vehicle ownership, travel mode for
all trips and travel mode for work trips, and transit usage is performed. The comparative analysis
would reveal facts beyond intuition which is essential in successful development of TOD and
transit policies.

The trip generation model, as the second objective of this paper, is to outline an easy to
replicate methodology that will enable transportation practitioners accurately forecast vehicular
trips associated with TODs. The development of a simple linear regression model consistent
with industry standard-of-practice is long over-due and this paper intends to fulfill this gap.

**PROBLEM STATEMENT**

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 and the type of roadway, the number of vehicles utilizing a roadway differs.

While the TODs have been extensively deployed and their behavior is well researched
and modeled outside the United States for many years, the concept is novel amongst
transportation policy makers and developers in the United States. Travel behavior associated
with TODs is often associated with strong assumptions, myths and/or intuitions and requires
further examination.

Furthermore, and most recently, several attempts have been made to determine the trip
generation of TODs. The Institute of Transportation Engineers (ITE) Trip Generation Handbook
is the primary source for calculating trip rates associated with a variety of land use. 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. The selection of the independent variables is usually based on accuracy, ease of data collection and reliability of the data. While ITE’s Trip Generation Handbook contains a trip rate for over 150 different types 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 element of transit is not necessarily an integral part of the proposed methodology and is not the primary focus in the model development process. Furthermore, the data utilized for the study was primarily obtained from suburban sites with abundant parking space. The methodology has been noted by many researchers and public organizations to overestimate trip generation numbers which leads to exaggerated roadway impacts and therefore higher impact fees. Consequently, developers have not been encouraged to develop this type of land use and take advantage of the lower impact fees it offers.

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 is needed. The data set for the proposed methodology should include factors that impact trip rates in a transit-oriented environment such as density and diversity of the land use, scale of the development, demographics, and distance to the transit station.

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 in areas with good transit network coverage 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).

Similarly, 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 (Kimley Horn and Associates, 2009).

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 followed the guidelines of ITE Trip Generation Handbook, 2nd Edition, for establishing local trip rates. The trip generation rates developed as part of this study was based on the empirical data that was collected from the 27 sites. The results of the study showed that the trip rates were substantially lower than the trip rates recommended by the ITE methodology (Caltrans, 2009).

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

Another methodology to accurately predict the traffic impacts of mixed-use developments with presence of transit was developed in a national study for the US EPA, performed by a team composed of both Fehr & Peers and academic researchers. The methodology is known as the “MXD Methodology” and is developed using the “D variables” associated with a land use. The original three Ds, density, diversity, and design created by Cervero and Kockelman (1997), followed by destination accessibility, distance to transit, and demographics (Ewing and Cervero 2001) which was developed later.
The MXD Methodology basically computes daily trip estimates using standard ITE rates or equations and then determines the probability of a trip staying internal to the mixed-use development (P\textsubscript{internal}), the probability an external trip will be made by walking or bicycling (P\textsubscript{walkbike}), and the probability an external trip will be made by transit (P\textsubscript{transit}) using user input information.

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

$$\text{Mixed-Use/TOD Development} = \text{Raw Trips} \times (1 - P\textsubscript{internal}) \times (1 - P\textsubscript{walkbike} - P\textsubscript{transit})$$

The three probability models (P\textsubscript{internal}, P\textsubscript{walkbike}, and P\textsubscript{transit}) depend on variables that are characteristics of the mixed use development which 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.

While the accuracy of MXD methodology is undeniable, the methodology involves numerous data input that is often complex and cumbersome to collect. The data requirements are in contrast to the state-of-practice. Most of the data requires additional data refinement that often involves the use of GIS and robust knowledge of database software. Transportation practitioners often perform the analysis speculating the data which would result in subjective inaccurate trip rates.

Another 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).

This research examines the travel behavior of TOD residents and compares them with non-TOD areas in the National Capitol Region. The myths and intuitions are challenged and assessed. Vehicle ownership in TOD areas is determined and is compared with non-TOD areas. 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 determined for the TOD area and is compared with non-TOD areas.
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 regional trips 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.

The data used for this research 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 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 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 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 surrounding the transit station.

The Rosslyn-Ballston Metro Corridor in Arlington, Virginia which was selected as the test site exemplifies a well-defined transit-oriented corridor (Figure 1). The corridor contains five metro transit stations that are well served by a reliable high speed underground metro-rail as well as surface street bus transit network. 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 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).

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.

1. The trip file from the MWCOG trip diary survey data is used to extract trips 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 number of 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.
TOD TRIP BEHAVIOR

The wealth of information contained in the 2007-2008 Household Travel Survey Data from the Metropolitan Washington D.C. Council of Governments (MWCOG) utilized for this research 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 this section myths and/or intuitions about TODs is examined.

The initial issue being investigated is that presence of transit facilities tends to reduce vehicular trip rates in commercial, office, and residential developments. Intuitively residents in a TOD environment tend to use transit for daily activities and the need to own a personal vehicle is diminished.

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) so that the comparison is unbiased.

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 which offers a reliable, well covered transit network to its residents. The mix-use developments adjacent to conveniently spaced transit stations service by the Washington Metro constitute the TOD segment of this analysis.

The non-TOD segment, however, is a typical suburban environment which the land use is predominantly constituted by single family homes, large lots, and plentiful parking spaces. 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 that portrays this type of land use.

The two areas are somewhat identical in terms of the employment population and are only within 10% of each other.

Examination of the data indicates that vehicle ownership is much less in a TOD zone than the Non-TOD zone. In Rosslyn-Ballston corridor where strong TOD community exists, the data terminates after the “5 vehicle” category indicating that no household has five (5) or more vehicles. Furthermore, the number of households in the TOD zone with no vehicles far exceeds the same category in the non-TOD zone. An interesting observation associated with vehicle ownership in TOD zones is that majority of residents own at least one vehicle. This questions total reliance on transit use in TOD zones. Had this been the case, the number of people with no vehicles would have exceeded all other categories of vehicle ownership in TOD zones. Since the data shows the contrary, further examination of data is triggered. Figure 2 shows graphical results of the analysis.
To further examine the extent of personal automobile usage in TOD zones, a comparative analysis of TOD vis-à-vis non-TODs with respect to detailed travel mode is performed. It is important to note that the TOD trips include trips that are either within a TOD zone or only one trip end is inside a TOD zone. However, non-TOD trips only include trips that are completely outside a TOD zone.

Intuitively the rate of use of transit should far exceed any other mode both inside and outside TOD zones. As Figure 3 shows, the rate of use of transit within TOD zones far exceeds non-TOD zones. Similarly, the rate of use of personal vehicles in TOD zones is lower than non-TOD zones. However, a surprising element is the higher rate for use of personal vehicle as opposed to transit usage inside TOD zones. A primary contributing factor may be the TOD zone data includes trips with one trip-end in a non-TOD zone. 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 the trip origin is 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, its lack of complete service coverage to all areas of MWCOG results in higher use of vehicle mode even in TOD areas.
As a cross check for the results obtained and shown in Figure 3, the data is further examined to only include home-based work trips. Work trips are especially important as they constitute majority of daily trips. For this analysis data coverage was expanded to include all 86 Washington Metro transit stations, and not just the Rosslyn-Ballston corridor. All home-based work trips within the 0.25 mile radius of a transit station were selected as trips inside a TOD zone. All home-based work trip-ends beyond 0.25 mile radius of a transit station are considered trips in 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.

Figure 4 shows results of the data associated with primary travel mode for home-based work trips. As the figure shows 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. There is heavier transit usage in TOD areas as home-based work trips are mainly performed via the use of transit. Furthermore, walk and bike, as the primary mode of travel, are more predominant in TOD areas than the non-TOD areas.

Consistent with the results obtained for the comparative analysis of vehicle ownership and detailed travel mode, the use of personal vehicle inside TOD area is still higher than the use of transit.
The higher use of personal vehicles in TOD zones can be contributed to the data refinement process where a trip with only one trip-end in a TOD zone is considered a TOD trip. There are numerous instances which the traveler may reside in a TOD zone, but work in a non-TOD zone, hence the higher use of personal vehicles. Furthermore, lack of complete transit coverage, especially in major residential suburbs such as Loudoun County, Virginia, is a contributing factor to the higher use of personal vehicles even in a region with substantial investment in modern rapid rail transit facility.

**CONNECTIVITY AND TRANSIT SUCCESS**

As the comparative analyses presented in the previous section show, examination of the 24-hour activity-based household travel survey from several perspectives indicate the strong association of transit network coverage and ridership. Auto dependency will not decrease if only one trip-end is in a TOD area. Travelers are forced to take personal vehicles for daily commute to work, even though the decision to reside in a TOD area has been a matter of choice.

Transit network coverage and the level of connectivity of transit routes are essential in a successful implementation of a transit policy. Ease of transfer from one transit route to another and the reliability of transit service encourages increase transit ridership as it provides a robust alternative in competition against the use of personal vehicle.
Service coverage has already been determined as an important factor in transit quality of service (TCRP Report 100, 2003). Complete regional coverage of a transit system that may include an integrated system of high speed rail, bus, streetcar, and shuttle is equally fundamental in increase ridership and thus a reduction in vehicular trips.

A SIMPLIFIED TOD TRIP GENERATION MODEL

A simplified and yet reliable model with relatively fewer inputs than current methodologies would be of interest to many transportation planners. The trip generation characteristic of TODs is best described by a linear regression model that is developed as part of this research. The regression model will enable traffic engineers and transportation planners accurately forecast vehicular trips associated with TODs. The regression format is consistent with the industry state-of-practice; a format that practitioners are accustomed to for forecasting many different types of land use.

Utilizing the activity based 24-hour household travel survey described earlier, the regression model is developed and validated relating TOD trip ends to gross floor area (GFA), in square feet. The validation of the regression model is performed by checking for normality of the distribution of data, multicollinearity and heteroscedasticity of the independent variables. The model used the development area (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 trip-ends in the same buffer zone served as the dependent variable.

The regression equation expresses the mathematical relationship between the dependent and the independent variable to predict the number of trip-ends generated by a TOD. It is basically the equation of a line that best fits the data points which in this case represent the gross floor area of a TOD in thousands of square feet.

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. Furthermore, the Central Limit Theorem ensures normality given the random selection of the independent variables.

The research hypothesis for the 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 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.

Let $\alpha = 0.05$ is assumed to be used for comparison with the P-value as a measure of how reliable the independent variable predicts the dependant variable.

Results of the analysis show a very small p-value (0.0000) indicating 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. Hence, the null hypothesis ($H_0$) is rejected.

Furthermore, the $R^2$, as the “measure of goodness of fit”, is 63%. The value of $R^2$ 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. Figure 5 shows the regression graph of this analysis.

![Linear Regression Graph – TOD Trips](image)
The association of trips in a TOD corridor and size of the development 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 (‘000 SF)

In addition to the sheer amount of data points that guarantees normality, normality of residuals is determined. The analyses was performed utilizing Stata® statistical software package. Figure 6 shows that the residuals are close to a normal distribution, thus we accept the independent variable to be normally distributed.

Heteroscedasticity, as another validation criterion for the regression model is performed. Heteroscedasticity is the test for homogeneity of variance of the residuals. If the model is well-fitted, then there should be no particular pattern between the residuals and the fitted values. 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 the residuals versus fitted (predicted) values is plotted using Stata.
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 7).

![Heteroscedasticity Test](image)

**Figure 7.** Heteroscedasticity Test

### MODEL VALIDATION

In addition to mathematical validation of the model shown in the previous section, 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 ITE trip generation for office use that is calculated based on the conventional methods prescribed by the latest edition of ITE Trip Generation Handbook. The independent variable is the Gross Floor Area (GFA), in 1000’s square feet, of a general office building (ITE Land Use Code 710) and the dependant variable is the number of trips ends. The ITE equation for this type of land use has a regression coefficient factor $R^2 = 0.8$ as follows:

$$\ln(T) = 0.77\ln(X) + 3.65$$

Where:
The MXD methodology, developed by the U.S. Environmental Protection Agency (EPA), is a substitute to the ITE multi use method. The methodology tends to reduce the vehicle trip estimates to better illustrate the trip generation behavior of mixed-use transit oriented developments. It is an MS-Excel spreadsheet based and requires various types of input associated with density, demographics, distance to transit and other land use measures. Key inputs to the spreadsheet are in the number of intersections 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 MXD methodology is the percent reduction of trips ensued by internal capture trips and external transit and pedestrian / bicycle trips. These trip reductions are subtracted from the regular ITE trip rates that are used as the base gross number of trips.

Results of the comparative analysis are shown on Table 1 which illustrates the comparison between all three methodologies.

<table>
<thead>
<tr>
<th>Table 1. Validation Test†</th>
<th>TOD Regression Model</th>
<th>Regular Non-TOD ITE Rate</th>
<th>MXD Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trips</td>
<td>5546</td>
<td>7856</td>
<td>4617</td>
</tr>
<tr>
<td>Difference</td>
<td>30%</td>
<td>7%</td>
<td></td>
</tr>
</tbody>
</table>

The developed regression model shows a 30% trip reduction for transit oriented developments compared to a non-TOD development. This is consistent with the state of practice. Furthermore, the results of the developed regression model are very much 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 mixed use developments 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.

† Based on 1,000 KSF of office use.
CONCLUSION

Current trip forecasting models developed for transit oriented developments are either inaccurate or require extensive data input. Consequently, transportation practitioners have been reluctant to fully utilize these models in their traffic impact studies. A simple, yet reliable methodology for determining vehicular trip generation rate for TODs is developed using activity-based 24-hour household travel survey data. Furthermore, comparative assessment of TOD vis-à-vis non-TODs with respect to trip rates, transit usage, and primary travel mode for home-based work trips is performed.

A regression model relating TOD trip ends to gross floor area (GFA), in square feet, for mixed land use was developed and validated. The validation is performed by checking for normality of the distribution of data, multicollinearity and heteroscedasticity of the independent variables. The model behavior is consistent with the industry state-of-practice. It will assist transportation practitioners accurately forecast trip generation rate for TODs.

The model is further validated against two state-of-practice measures for trip prediction. The developed regression model shows a 30% trip reduction for transit oriented developments compared to a non-TOD development. This is also consistent with the state of practice. There is less than 10% difference in trip generation numbers between the developed regression model and the MXD methodology, which further affirms the validity of the model. An essential step in validating the model using actual trip generation rates is suggested as future work.

Results of the data analysis associated with vehicle ownership, and mode split for all trips and in particular work trips are intuitive. 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.

However, contrary to intuition, the use of personal vehicle in TOD areas for different trip purposes is still high in comparison with transit use. This is because while residents of the greater Washington D.C. area enjoy a world class transit operation, yet the transit network is not fully saturated and only serves a limited part of the geography. Trips with one trip-end in a non-TOD zone forces the traveler to utilize the personal vehicle for various activities particularly work trips.

Transit network coverage and the level of connectivity of transit routes are essential in a successful implementation of a transit policy. Ease of transfer from one transit route to another
and the reliability of transit service encourages increase transit ridership as it provides a robust alternative in competition against the use of personal vehicle. Service coverage has already been determined as an essential criterion in the assessment of transit quality of service. Limited service coverage reduces the ability of suburban areas that have implemented smart growth strategies to reduce vehicle trips.

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.
ACKNOWLEDGMENT

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REFERENCES

10. NCHRP 406: “Advanced Practices in Travel Forecasting” Transportation Research Board, 2010
LIST OF TABLES AND FIGURES

TABLES

Table 1. Validation Test ................................................................. 19

FIGURES

Figure 1. Study Area for Trip Generation Model................................. 10
Figure 2. Vehicle Ownership – TOD vs. Non-TOD ............................. 12
Figure 3. Detailed Travel mode – TOD vs. Non-TOD .......................... 13
Figure 4. Work Trip Estimation Per Primary Travel Mode – TOD vs. Non TOD ....... 14
Figure 5. Linear Regression Graph – TOD Trips..................................... 16
Figure 6. Normality Test of Residuals .................................................. 17
Figure 7. Heteroscedasticity Test ...................................................... 18