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# STATE HIGHWAY ADMINISTRATION

# RESEARCH REPORT

# DEVELOPMENT OF A FRAMEWORK FOR TRANSIT-ORIENTED DEVELOPMENT (TOD)

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| 16.Abstract<br>In this project, a comprehensive analysis of TODs in the Washington, D.C., and Baltimore metro areas was performed to investigate if TOD can reduce automobile travel and encourage transit use as well as non-motorized modes. The research team modeled vehicle-miles travelled (VMT), trip generation, trip length, and mode share in two case study areas using the most recent local household travel survey data and advanced econometric models. Findings show that people living in TODs overall have lower household VMT, make more trips by all modes of transportation, but make fewer trips by automobiles. Results also show that TOD residents tend to travel shorter distances by all modes of transportation, which implies their selection of closer destinations for their activities. Trips originating from TODs have substantially higher non-auto mode share in both areas after controlling for relevant socioeconomic and demographic factors. The study also finds significant differences in the effectiveness of TODs in these two metropolitan areas due to different TOD locations, transit system availability and level of service, and TOD resident characteristics. As a result of this study, SHA will be able to incorporate the effect of TOD on a transportation system into the trip generation, distribution and model choice steps of the Maryland Statewide Transportation Model (MSTM). | | |
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## EXECUTIVE SUMMARY

In this project, the research team performs a comprehensive analysis of transit-oriented developments (TODs) in the Washington, D.C., and Baltimore metro areas to investigate if TODs actually can reduce automobile travel and encourage transit use as well as non-motorized modes. The research team modeled vehicle miles traveled (VMT), trip generation, trip length, and mode share in two case study areas using the most recent local household travel survey data and advanced econometric models. Findings show that people living in TODs have lower household VMT, make more trips by all modes of transportation, but make fewer trips by automobiles. Results also show that TOD residents tend to travel shorter distances by all modes of transportation, which implies that they choose closer destinations for their activities. In terms of mode choice, trips originating from TODs have substantially higher non-auto mode share in both Baltimore and Washington, D.C., after controlling for relevant socioeconomic and demographic factors. The research team also finds significant differences in the effectiveness of TODs in these two metropolitan areas due to different TOD locations, transit system availability and level of service, and TOD resident characteristics. As a result of this study, SHA will be able to incorporate the effect of TOD on a transportation system into the trip generation, distribution and model choice steps of the Maryland Statewide Transportation Model (MSTM). The results demonstrate that TOD areas have different trip rates and travel behavior. Therefore, developing transportation models that separate TOD from Non-TOD areas would yield more accurate results than the current models. Using such models, sensitivity analysis for changes in TOD characteristics would become possible.

# INTRODUCTION

Transit-oriented development (TOD) is a type of development that encourages public transit and a transit-friendly urban environment. TODs are fast-growing developments nationwide and statewide. In Maryland, many TODs have been proposed or built because of smart growth strategies. TODs are moderate to high density, mixed-use, and walkable developments with easy access to major transit hubs. In theory, they can greatly reduce the need for driving, increase multimodal mobility, reduce air pollution and greenhouse gas emissions, and reduce long-term highway infrastructure needs.

TODs could also reduce the number of auto trips by providing better accessibility to jobs and other destinations, and encourage sustainable modes of transit, walking, and biking by facilitating a pedestrian-friendly environment and transit services.

When planning, designing, and assessing TODs, their impact on travel behavior, mobility, and sustainability should be considered and incorporated into the decision-making process. However, there are currently no guidelines on how to successfully develop TODs or standard tools for TOD evaluation in Maryland.

This project developed a data and analysis framework for TODs in Maryland. TOD is defined using land use characteristics of the neighborhoods such as residential and employment densities for each transportation analysis zone (TAZ), the level of land use diversity, street connectivity, and pedestrian-friendliness. The project analyzed the impact of TOD on travel behavior and on transportation systems. It also analyzed the impact of behavioral changes induced by TOD on congestion, pollution and greenhouse gases (GHG) emissions, and other sustainability indicators, and calculated the monetary value of this impact.

## LITERATURE REVIEW

Over the years, various terms have been used to refer to transit-oriented development concepts: transit village, transit-friendly design, and transit-supportive development. However, TOD is the most widely used term. This topic has been analyzed and evaluated to observe the procedures for making TODs successful. Over the past few decades, transit agencies have been working with the private sector and government agencies to study and plan TODs. Planners, researchers, and practitioners have proposed several different definitions for TOD that vary in scope and specificity. However, most of these definitions share basic elements. Calthorpe (1993) defined TOD as "moderate and high-density housing, along with complementary public uses, jobs, retail and services, concentrated in mixed-use developments at strategic points along the regional transit systems." He summarizes the main characteristics and goals of TOD as follows:

- organize growth on a regional level to be compact and transit-supportive
- place commercial, housing, jobs, parks, and civic uses within walking distance of transit stops
- create pedestrian-friendly street networks that directly connect local destinations
- provide a mix of housing types, densities, and costs
- preserve sensitive habitat, riparian zones, and high quality open spaces
- make public spaces the focus of building orientation and neighborhood activity
- encourage infill and redevelopment along transit corridors within existing neighborhoods

In general, TOD provides an environment where residents live within walking distance of a major transit station and different amenities. In order to have a successful TOD, planners need to find sites that are potentially suitable.

Station-area planning for TOD includes planning for zoning, design, parking requirements, and transit, bike, and pedestrian facilities (Reconnecting America, 2009). It provides the plans that can define the timeframe and strategies for implementation. Overlay zoning is a mechanism that can help to initiate plans for the sites. The Center for Land Use Education (2005) defines overlay zoning as "a regulatory tool that creates special zoning district, placed over an existing base zone(s), which identifies special provisions in addition to those in the underlying base zone." Overlay zoning has similar objectives as TOD, such as the decision to create high-density areas, affordable housing, and many other attributes. Land-use planning is an important aspect of station planning because the land must meet the government's and developers' criteria in order to receive TOD investment. The design must be able to target adequate ridership and walkability within the station area. Providing incentives to encourage people to take transit is a key element for TOD. Without enough incentives, many people will drive their cars and may not consider alternative modes such as transit, walking, or cycling.

A TOD's structure is made of local and regional elements that need careful consideration, from population and demographic characteristics to accessibility (to jobs, education, shopping, recreation, services, and other opportunities). TOD implementation needs to ensure that goals, such as improving accessibility and alleviating sprawl, will be met. The Transit Cooperative Research Program (TCRP, 2007) emphasizes that high transit ridership is a significant factor for a TOD's success. For example, in Washington, D.C., the opening of a metrorail heavy rail transit

(HRT) station increased ridership by 56 percent within one year. It also found that people in San Francisco who lived near transit were more likely to commute by transit (Cervero, 1994). Reducing urban sprawl is a significant factor for a TOD as it can encourage alternative modes of transportation. Accommodating walking to and from transit stations is another way to increase transit ridership. Cervero (2004) stated that mobility and layout are key elements to targeting walkability. Implications for TOD need to be carefully planned to examine how well each goal can be met by different agencies.

To have a successful TOD, cities need to develop conceptual land use plans and a development scheme, streetscape and design guidelines, priority infrastructure investments, and a financial plan. Plans should include housing types and affordability, commercial uses, business attraction and mixes, and job location. However, they should be flexible enough to allow for creativity, originality, and affordability (Reconnect America, 2006).

Figures 1 and 2 present a TOD concept suggested by Calthorpe (1993). In this concept, retail shops and services are in a commercial core within an easy walk of homes 0.37 miles (600 meters) or about ten minutes.

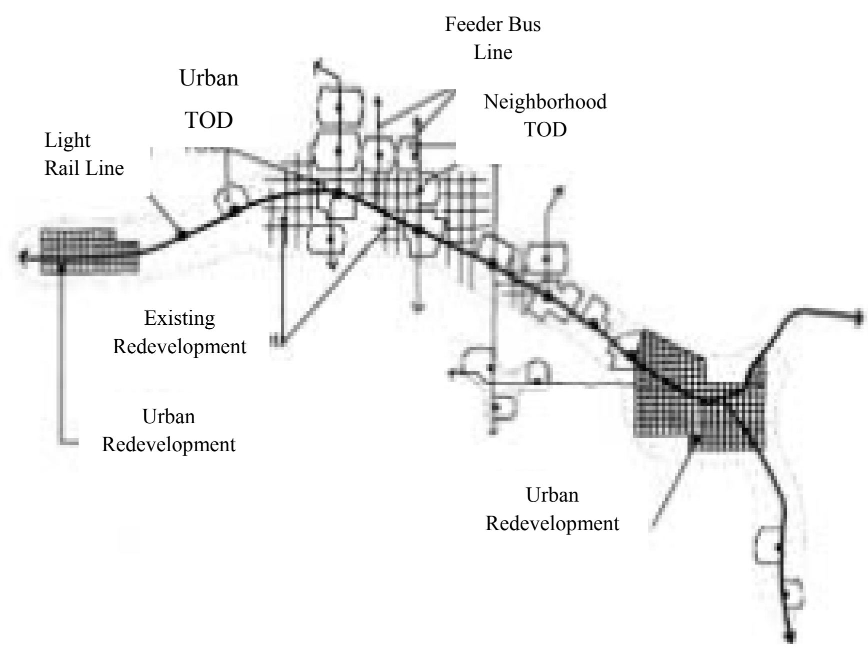



**Figure 1. Calthorpe's Conceptual Model of TOD Planning (Calthorpe, 1993).**

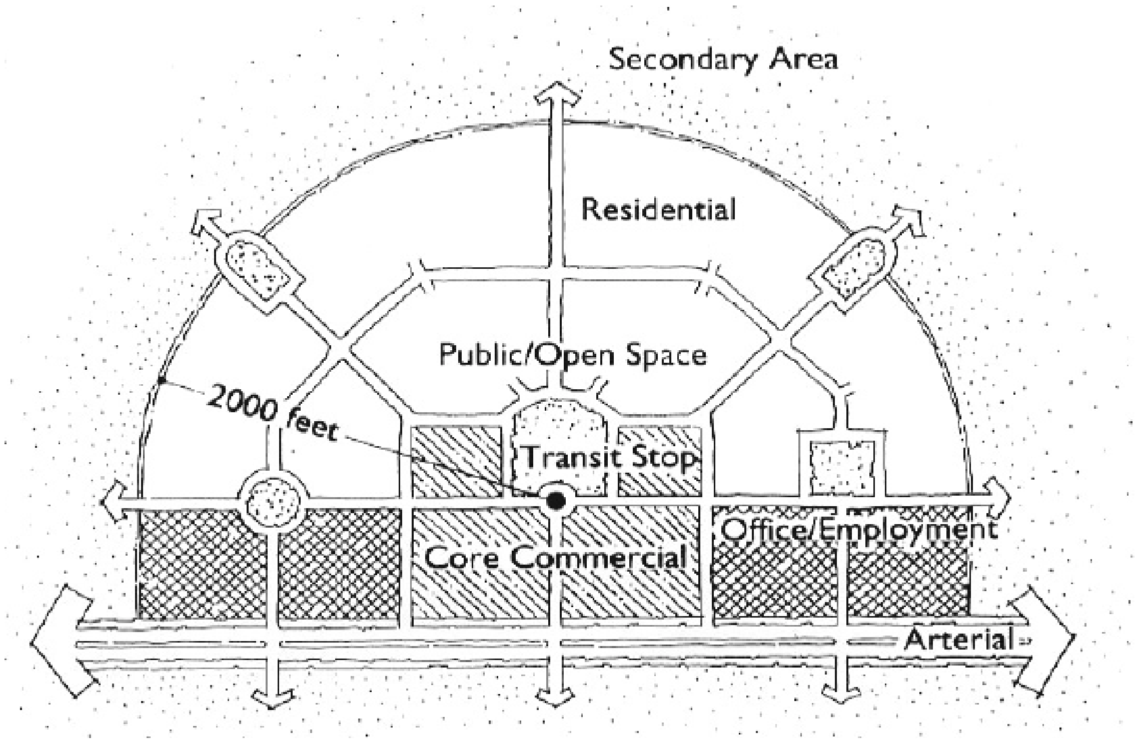



**Figure 2. Calthorpe's Conceptual Model of a Walking-Scale TOD (Calthorpe, 1993).**

**TOD Definition**

The research community's present state-of-knowledge on TOD provides various definitions for a TOD based on different viewpoints and perspectives. Some define it simply as a high-density area located within walking distance of a transit station (CTOD, 2013), and some highlight the walkability factors as well as high-density and mixed-use aspects. By doing so, they define a TOD as a high-density area where there are shopping, housing, and employment opportunities available, designed for pedestrians without excluding the automobiles. Others focus on how well the collaboration of land uses and transit work and identify a TOD as a "development with a functional relationship to transit, allowing it to achieve synergies that enhance the value of both" (Fastracks, 2008).

Calthorpe (1993) defined a TOD as "moderate and high-density housing, along with complementary public uses, jobs, retail and services, concentrated in mixed-use developments at strategic points along the regional transit systems." More recently, Parker et al. (2002) defined the concept of 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."

Most of the theoretical definitions proposed for a TOD in the body of literature share a few main elements. These elements include (1) compact mixed-use development, (2) pedestrian friendliness, and (3) neighborhoods well-served by transit. In practice, there are different approaches proposing different quantitative measurement criteria for a TOD. Bernick and Cervero (1997) have specified a half-mile buffer zone around a transit station as a TOD. They defined a TOD as "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."

Lund et al. (2004) also emphasized designing and developing TODs to accommodate both motorized and non-motorized modes and suggested that it is possible to encourage pedestrian trips without discouraging automobile traffic by creating street networks that allow safe and efficient interaction among all these modes.

**TOD Location**

Urban areas and city centers can potentially be a TOD. These areas have sites for either infill development or expansion of existing or proposed transit stations. Typically, this TOD context tends to be situated near or within downtown areas, central business districts, airports, malls, and other places that have a high capacity for trip generation. In Washington, D.C., for example, the Gallery Place Metrorail HRT is located downtown and provides people with access to the city's basketball and hockey arena (TCRP, 2007). TOD planning could also be focused on improving connectivity among areas that generate activities. For instance, in Cleveland, Ohio, the bus rapid transit was constructed to connect the two largest employment centers, Central Business District and University Circle, to other public spaces (Vincent and Jerram, 2008). Many urban areas are primarily focused on the downtown area because of its higher rate of generated activities, which can potentially lead to a successful and effective TOD.

Suburban areas, typically auto-dependent and low-density areas, have been considered very broadly in the majority of TOD implementation plans. The suburbs usually have available land to develop transit stations. For instance, the end of the line on San Francisco's Bay area rapid transit (BART) is a suburban station in Pleasant Hill, California. The Pleasant Hill station is surrounded by many office spaces, hotels, residential units, retail, and surface parking.

Because of high automobile dependency in suburban areas, feeder buses tend to be inadequate and a park-and-ride station would suit these particular station areas (TCRP, 2004). It is very important that TOD plans provide benefits for the suburbs that encourage people from all social classes to live in the area. In order to influence homebuyers' decisions to buy houses in those areas, tools that enhance the suburban TOD context are needed. In Atlanta, transit agencies have taken measures to facilitate a TOD environment due to the amount of sprawl and pollution emissions. The Atlanta Regional Commission studies suggest that the region become more transit oriented by incorporating the following methods: connecting land uses, increasing streetscapes and sidewalks, putting an emphasis on pedestrian movement, improving accessibility, providing various mode choice alternatives, and expanding housing availability and affordability (Goodwill and Hendricks, 2005).

A general inventory map of TOD funding programs (fund TOD plans and projects) throughout the United States is presented in figure 3. There are 42 TOD programs: 18 state-level, 15 regional and transit agency, and 9 local programs. Each dot may represent more than one program.

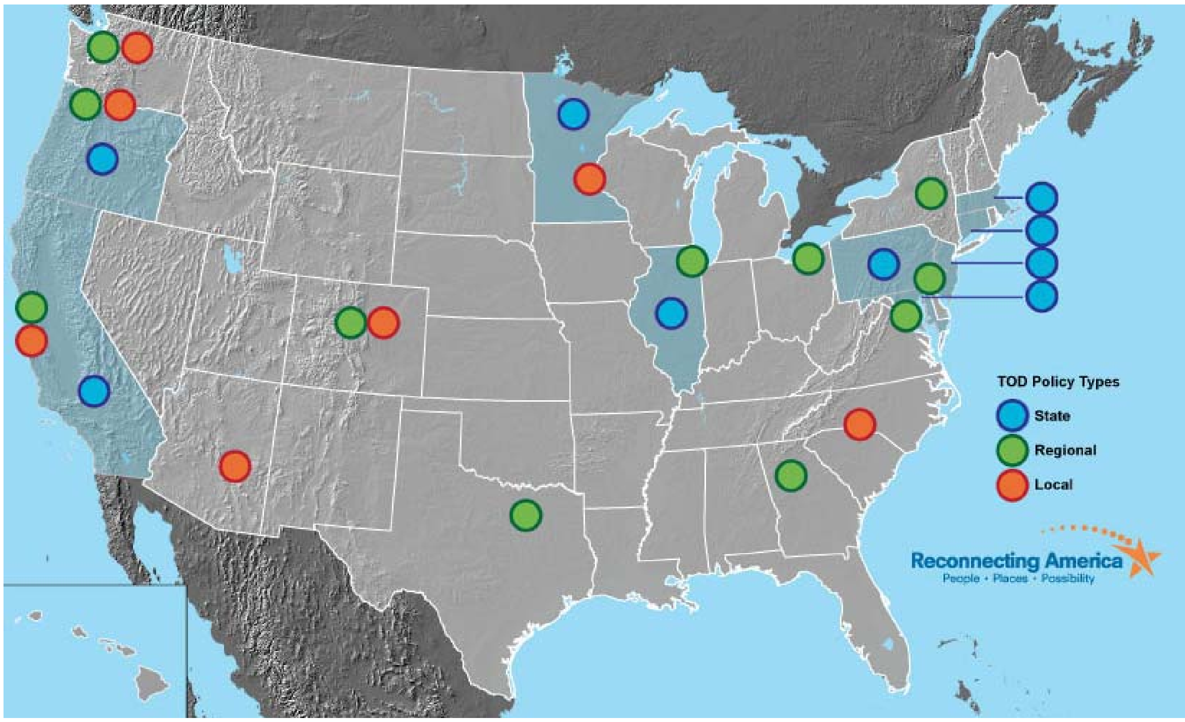



**Figure 3. Inventory Map of Nationwide TOD Programs (Reconnect America, 2012).**

### Low-Income Groups and TOD

Transit-oriented development tends to target medium- to high-income neighborhoods as they are more desirable for developers to potentially make investments. Developers are not interested in making investments in low-income neighborhoods because they are not as promising in terms of profit as are high-income areas. However, based on environmental justice, low-income areas should be a primary consideration for TOD since they are not as auto-dependent as other areas with higher car ownership rates. If these areas are targeted for TOD planning, gentrification may occur and people of low income will be moved farther away from comprehensive transit services. There are strategies that can help to preserve low-income households in these areas. In Denver, a comprehensive plan incorporated low-income housing in TOD areas. The plan aimed at producing mixed-income TOD and explored different options to provide affordable housing (City and County of Denver, 2006). Other tools to encourage TOD in low-income areas include a low-income housing tax credit (LIHTC), wherein developers provide 40 percent of units at 60 percent of the area's medium income (AMI) or 20 percent at 50 percent of the AMI (Shoemaker, 2006). The developers agree to fix the rent at an affordable rate for 15 years or more (Shoemaker, 2006).

As mentioned above, providing affordable housing is a very critical issue in planning for TOD. Providing affordable housing near transit stations could provide easy access to transit for households (for all trip purposes) and also increase the transit ridership. A community benefits agreement (CBA), a mechanism to provide affordable housing, is defined as a private binding contract between the developer and the community that requires the developer to demonstrate how the proposed project will benefit the community (Soursourian, 2010). In Minneapolis, Minnesota, the Longfellow neighborhood CBA was able to preserve 30 percent of affordable housing for its low-income residents and 50 percent for middle-income residents (Soursourian, 2010). Other mechanisms, such as housing funds, have also been used to provide affordable housing for low-income residents around transit centers. Charlotte, North Carolina, established a publicly funded housing trust that was handed over to a private developer to preserve affordable housing (Reconnecting America, 2009). Affordable housing increases the likelihood of establishing TODs. Enticing developers to preserve housing is important, and tax abatement is generally an appealing incentive. The state of Oregon allowed property tax abatements for ten years to multi-family housing near transit to help preserve affordable housing (TCRP, 2002).

Another tool that can encourage residents to live near transit is Fannie Mae's location efficient mortgage (LEM) program. The LEM program encourages homebuyers to purchase homes near transit by offering larger loans and lower down payments (Hendricks et al., 2002). In Seattle, if homebuyers (of all income levels) agreed to own one car and live within one-fourth of a mile of a light rail or train station, they received a two-year, 25-percent discount on bus passes, and free membership and discounted fees for Flex car car-sharing (Hendricks et al., 2002).

When inefficient and poor housing policies increase housing prices where transit is provided, TODs are less likely to succeed. For example, Orenco's station in Portland, Oregon, failed to provide affordable housing and the prices went up 30 percent over the county average (Cervero, 2004).

**Community Involvement**

A community's involvement in TOD planning can facilitate a better environment for residents, tourists, and commuters, and the community can potentially take a proactive role to secure development opportunities that fit its needs. The Hiawatha line in Minneapolis, as an example, was created to revitalize the riverfront district. The authorities spent much time and effort to build parks and public infrastructure along the line to ensure easy access to these public places (Austin and Fogarty, 2011). Outside of the city of Minneapolis, development efforts around the transit stations have not been the same, mostly because these areas have fewer infill sites and publicly owned properties. Efforts for community involvement include setting agreements with private owners to make investments on certain developments mainly to improve pedestrian facilities or preserve affordable housing. A community involvement example is the city of Denver, in which the public agreed to clean the area and preserve identical buildings (Austin and Fogarty, 2011). Other efforts, such as the Fruitvale in Oakland, California, involved providing sustainable housing for mixed-income households.

There are organizations that are geared toward community efforts, such as community development corporations (CDC). A CDC facilitates transit projects in areas where plans are not considered. This is useful for low-income areas, which are usually bypassed by the market (Reconnecting America, 2009). Bethel New Life, a CDC in Chicago's Lake Pulaski transit neighborhood, raised $10,000 from local churches to create a child care center and mixed-use area that revitalized the community (Reconnecting America, 2009). Community involvement, if combined with the efforts of regional and local governments and transit agencies, could be effective in creating a vision that does not hinder the construction process. In Raleigh, North Carolina, the transit agency and regional planning body appointed a citizens group to be in charge of proposing recommendations about the form of communities supported by buses and guide way services (TCRP, 1999). It would also be effective to improve and discuss transit-oriented development plans in public hearings where residents, agencies, and local governments meet to discuss various types of city-related issues.

**Streetscape and Urban Design**

One of the design principles of TOD is to improve the quality and safety of walking and cycling facilities. If pedestrians and transit development are disconnected, then the TOD may not be successful in the long run. Most U.S. cities use conventional Euclidian zoning that segregate incompatible land uses. However, this zoning is not suitable for TOD. Mixed-use zoning and form-based codes have been used by different cities to accommodate TOD.

Mixed-use zoning creates special zones or districts but doesn't change the underlying requirements of auto-dependent planning. Many cities prefer form-base codes to mixed use to achieve more vibrant and human-scaled neighborhoods. Form-based code focuses on the form of the built environment, regulating building height, windows and doors, and streets and sidewalks (Reconnecting America, 2009). Properly designed streets, blocks, and sidewalks provide a safe and attractive walking environment and accommodate sustainable transportation to and from transit stations in TOD areas. Researchers have identified many suburban and urban corridors that have developments surrounded by uninspiring streetscapes and inefficient connections to corridors (Calthorpe, 1993; Loukaiton-Sideris, 1993; Duaney et al., 2001). TOD planning needs to emphasize connectivity, safety, and accessibility. Wider sidewalks and streets that do not conflict with pedestrian activity make better streetscapes. TCRP (2007) stated that neighborhood vitality at the destination has a strong positive relationship to the choice of all non-auto modes examined (walk, bike, and transit) for most types of trips. Further analysis on the implementation of design and streetscapes shows that there is a positive relationship between proper urban design and transit use in TOD areas. Attractive pedestrian facilities and street furniture (i.e. fixed objects such as benches, traffic lights, bus stops, waste receptacles, statues, etc.), high street connectivity, and safely designed crosswalks could all play a significant role in increasing transit ridership and commuting trips (TCRP, 2007).

Southworth and Ben-Joseph (1997) and Schlossberg and Brown (2004) claimed that issues such as traffic congestion, air pollution, and low connectivity could be directly or indirectly linked to road network patterns. Schlossberg and Brown (2004) utilized three evaluation techniques to rank and compare the connectivity of 11 TODs in Portland, Oregon. The techniques were network classification, pedestrian catchment area (PCA), and impedance-based intersection intensities. Network classification categorizes street types and purposes within TODs. PCAs are theoretical walkable zones that can be mapped to present the actual area and network of walking distance to a transit station. Intersection intensity analysis concentrates on pedestrians, intersections, and dead-ends. Impedance-based intersection intensity analysis excludes freeways and major arterials and concentrates only on neighborhood road crossings. Based on the three aforementioned evaluation techniques, Schlossberg and Brown presented six measures: quantity of accessible paths, quantity of impedance paths, PCA ranking, IPCA ranking, intersection density, and intensity of dead-ends.

### Effects of Parking

Parking availability and management can be a challenge in TOD planning. While one of the most important purposes of TOD is to get people out of their cars, planners might still need to provide parking for people to get access to transit. Parking availability tends to be common in suburban areas in the form of "park and ride" policies, in which people park their car and use transit. In Seattle, the Puget Sound Regional Council (1999) recommended building parking structures and creating an environment that encourages walking. Parking should not overwhelm the area or create barriers for accessing the station. It is claimed that inadequate park and rides at TODs can reduce ridership (TCRP, 2007).There is a certain amount of parking that should be provided without disturbing the objectives of the TOD. Parking availability above that amount could result in transit ridership reduction at the stations (TCRP, 2007). Spacing is a critical factor for parking, as it could potentially prevent expansion and development of other land use types. For example, parking space along retail, office, and residential land uses will reduce the amount of space available to expand those land use types. In addition, parking spaces can increase the cost of a TOD, including the budget allocation for mixed-use development and streetscape improvements. For every parking space built, the budget increases $20,000 to $40,000 (Reconnecting America, 2009). TOD implementation in urban areas can reduce the amount of parking. TCRP (2007) reported that the parking reduction was 60 percent for a retail store in Pacific Court in Long Beach, California, and 17 percent for a general office in Portland, Oregon.

TOD intends to reduce vehicle miles traveled; thus; shared parking might be a cost-effective policy in TOD areas. It allows land uses to share parking spaces and increases the developments' vibrancy and land value (Reconnecting America, 2009). Shared parking allows the local jurisdiction to require regulations for designing this feature, such as pedestrian walking distances (Reconnecting America, 2009). If parking reduces transit ridership, then pricing policies can be implemented. TCRP (2004) found that 42 percent of station-area residents who paid for parking commuted by San Francisco's BART, while only 4.5 percent of those who enjoyed free parking commuted by BART. There is a direct relationship between free parking and ridership. The pricing can create incentives for people to use feeder buses instead of driving their cars, which reduces congestion around land uses. Parking needs to be conducted in a way that does not hinder the TOD's success. Certain developments will need parking due to the type of businesses they contain. Parking planning must be done in a way that does not lead to businesses moving out of the central district (Shiftan et al., 2003).

### Smart Growth Strategies

TOD has recently received a lot of attention as a tool to promote smart growth. Smart growth strategies revitalize areas, enhance the economy, and improve quality of life by enabling suitable arrangements for people. Smart growth policy defines land use mix, utilizes infrastructure and land, and attracts people to neighborhoods. Many cities have implemented smart growth initiatives in order to resurrect neighborhoods and stimulate their economy. Smart growth efforts have been developed in Owings Mills, Maryland, where the city is reusing station-area parking to develop an urban center that will stimulate mixed land uses (TCRP, 2002). It is important to make such investments so that businesses settle in cities and increase the number of jobs. People do not invest in an area where there is a low chance of activity generation and potential growth.

Smart growth policy spurs economic revitalization by creating mixed land uses that increase business opportunities, such as housing, nightlife services, and shopping (International Economic Development Council, 2006). A good example of smart growth strategies in a TOD area is Brewery Blocks in Portland, Oregon. This place was designed to include art galleries, nightlife, and loft apartments. In this project, the city tried to attract wealthier people so that they paid the cost of project through taxes. Silver Spring, Maryland, used smart growth strategies to bring new life to its downtown. It is connected to DC metro system and has become an attraction for economic activities and residential units. Public and private funding was received for the project and the development performed beyond expectations. The town center led to new projects and finally to attract Discovery communication that brought over 1,200 new jobs in downtown (International Economic Development Council, 2006).

Analysis of trip chaining is an important factor in TOD planning because a transit service that provides different options and better accessibility will encourage more transit trips. For example, in San Diego, many trolley stations are near daycare centers; thus, parents have the option to drop their kids off at the station and use transit for their work or non-work activities (TCRP, 2002). In the 1970s, new subway stations in San Francisco and Washington, D.C., failed to increase ridership due to a lack of sufficient housing or commercial development in the surrounding area (TCRP, 1995).

### Financing/ Leverages

Financing includes, but is not limited to, tax-increment financing (TIF), which is a tool used to obtain property tax revenue from the assessed value. San Francisco's Pleasant Hill BART station used this mechanism to pay for underground utilities, drainage, and a water system (TCRP, 2002). Another method that is similar to TIF is synthetic TIF, which allows developers to provide funding for the investment and in return receive back payments from the public sector through property taxes (Austin and Fogarty, 2011). Public-private partnership (PPP) is a common mechanism for TOD wherein both parties agree to pay for the cost. In Portland, Oregon, Brewery Blocks received a 36:1 ratio of private-to-public capital by using PPP plans. The redevelopment cost of Brewery Blocks was $300 million: the public invested $6 million in loans for the underground parking and $2 million for infrastructure improvements, and the rest came from the private sector (International Economic Development Council, 2006). PPP can prevent risks during the development process, and give the local government time to conduct community hearings, inspect construction, and work with banks to lower loan costs (Reconnecting America, 2009).

A joint development arrangement is a leverage that facilitates certain parts of TOD. Joint development involves a transit agency joining the private sector to work on publicly owned land. The developers bring their own resources, property, and knowledge to the project, and the transit agencies are able to market their idea to the developers (Reconnecting America, 2009). The Washington Metropolitan Area Transit Authority (WMATA) created a joint development guideline and policy to ensure a successful TOD. Some of the TOD guidelines consist of using smart growth strategies that alleviate automobile ridership, create pedestrian and bicycle trips, provide safety for station areas, include mixed-use planning, and enhance connections to the station area (WMATA, 2008). It is crucial to allocate resources and investments in a way that meets the needs of the community and ensures a successful TOD implementation. To make projects feasible, Cervero (2004) stated that financing is important for spreading risks and enhancing the base of knowledge and experience.

The availability of loans to fund projects near transit is based on market demand. Lenders may not even know that they are funding a TOD and rarely adjust lending standards to reflect proximity to transit.

Property tax revenue is a common financing tool that requires people moving into TOD residential housing to pay taxes that will help pay off the project cost. Affordable housing strategies, such as housing funds that include the private and public sectors' joint investments, are methods that can preserve housing in TOD areas. These funds can also come from real estate transfer taxes or documentary stamp taxes, both of which require the seller and buyer to pay a portion of the housing funds (Reconnecting America, 2009).

**Mobility Assessment Plan**

A mobility assessment plan (MAP) is a new method used as part of TOD planning. A MAP aims to examine future transportation demands on road networks by looking at connectivity among stations and communities, capital infrastructure, and mobility improvements (The City of Calgary, 2009). The plan includes goals for the MAP and provides sketches of where improvements need to be made. The Sunalta station in Calgary, Alberta, in Canada used a MAP to provide information on improvements that were needed. The goals for Sunalta's MAP involved community parking issues and transportation network improvements for vehicles, bicycles, and pedestrians (The City of Calgary, 2009).

**Challenges**

Incomprehensive plans and lack of leadership by local governments are some obstacles for TOD. Besides, transit development alone cannot drive real estate investments. Another obstacle for TOD is the "congestion conundrum," a nodal development where different spots of congestion occur as a consequence of TOD implementations (Cervero, 2004). Parking, as well, is a huge issue in implementing TOD plans. As stated earlier, there are several questions regarding parking with no or ambiguous answers: Should one create parking?  How much parking space should be available? Would the parking decrease or increase transit ridership? How do finance it?

Reconnect America (2006) states that the following are tools for a successful TOD: livable communities, station-area planning, community effort, right-sizing parking, shared parking, aesthetic zoning, collaboration (public private partnerships), joint development, land assembly, and housing trust funds.

**Maryland TODs**

The Maryland Department of Transportation (MDOT) is expanding towards a more pedestrian environment and increased transit ridership. Figures 4-6 display the progression of TOD mapping in Maryland as of April 2012. The information was taken from MDOT's website.

The definition of TOD varies among agencies in Maryland. MDOT defines TOD as developments of real estate within an appropriate walking distance of a transit station that will enhance transit ridership and alleviate dependency on cars (MDOT, 2010). WMATA (2006) defines TOD as a support of transit that stimulates available transit. In TCRP (2004), the Maryland Transit Administration (MTA) defined TOD as a high-density area with mixed land uses within walking distance of a bus or rail center (Cervero, 2004).

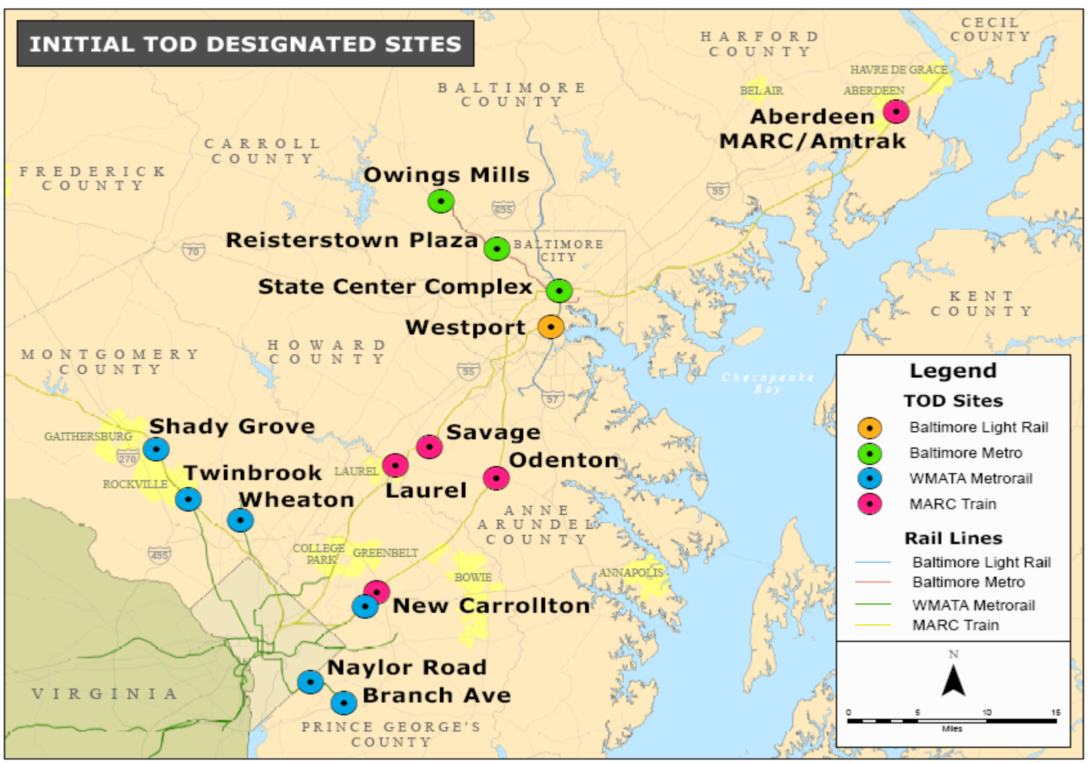



**Figure 4. Initial TOD Designated Sites in Maryland (2008).**

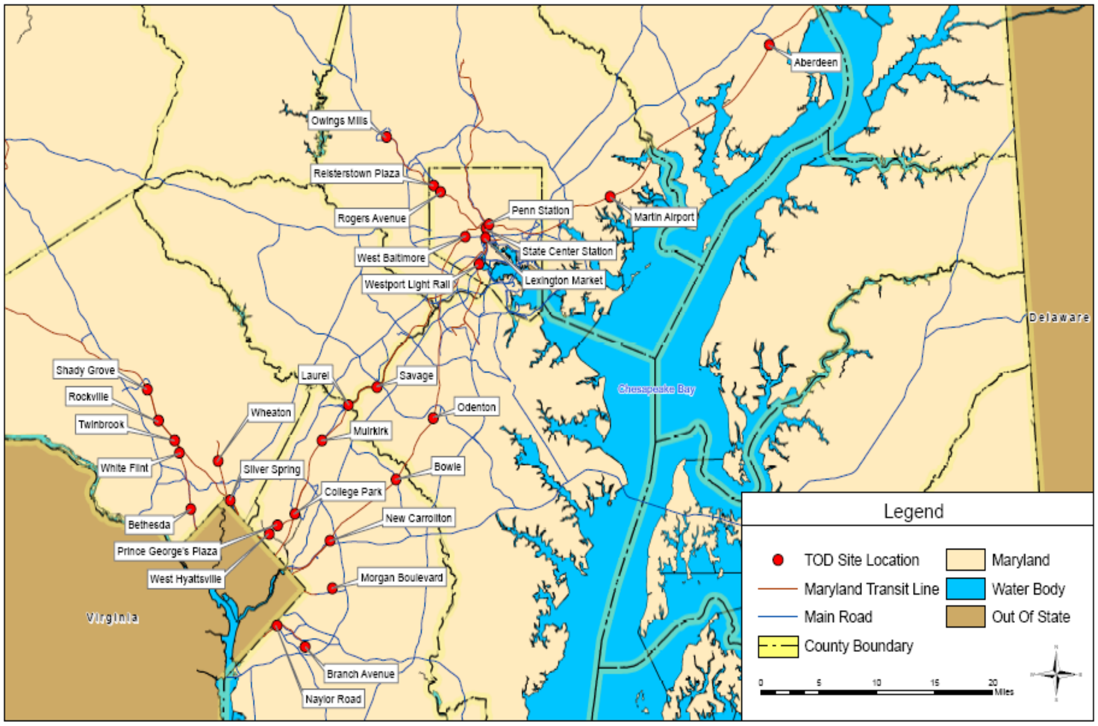



**Figure 5. TOD Activities in Maryland (2010).**

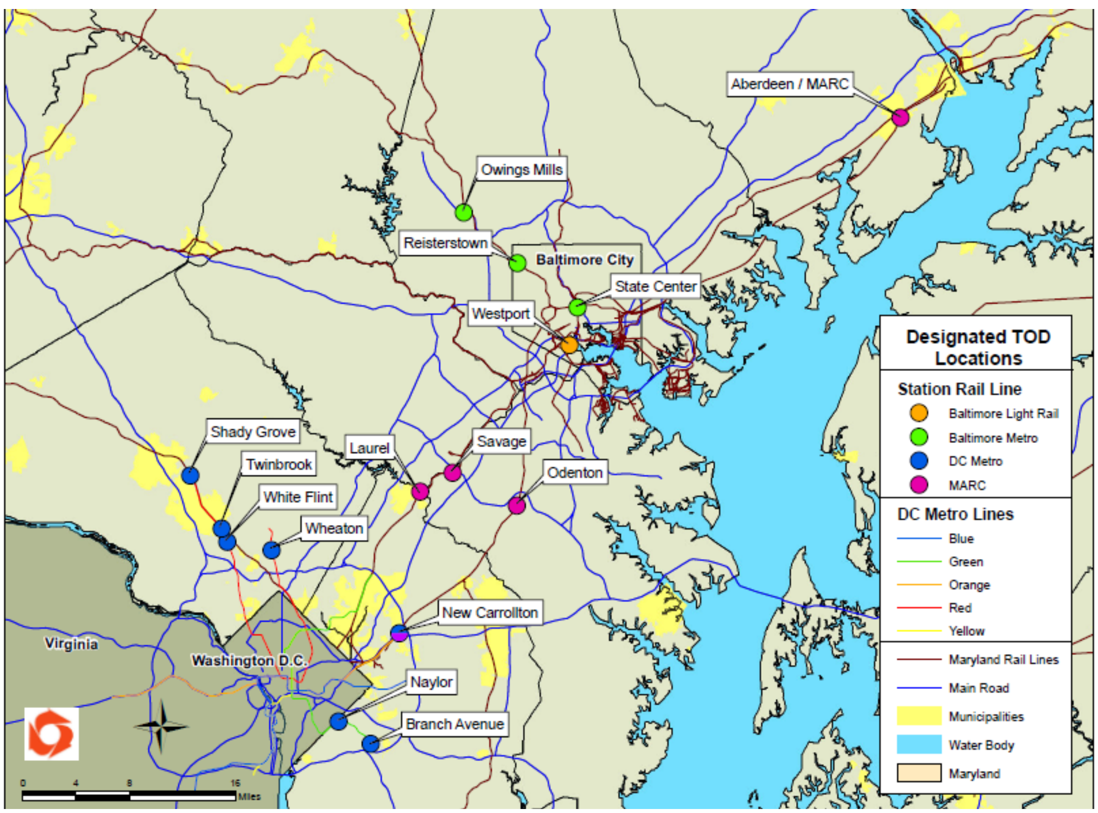



**Figure 6.Maryland's 15 Designated TOD Sites (2012).**

As of June 2012, Maryland had designated 15 TOD sites, which are as follows.

**Branch Avenue Metro (Prince George's County)**

The Branch Avenue Metro is located in Prince George's County. The approximately 38-acre site is on both sides of the elevated Metrorail Green Line tracks. Recent improvements on the Metrorail include tracks, surface parking lot, and a bus bay. Currently, there are no projects under construction, but WMATA is planning to create a joint development plan that will ensure that transit is a focal point (WMATA, 2012).

Status

- Predevelopment planning for joint development
- SHA design underway to improve access to station

State Assistance

- Nearly $5.5 million through fiscal year 2012, $9 million programmed for engineering and right-of-way acquisition in fiscal year 2013-2016

Unique Features

- Within an enterprise zone
- BRAC revitalization and incentive zone

**Naylor Road Metro (Prince George's County)**

The Naylor Road station TOD is expected to stimulate the economy. It incorporates developments that can generate trips and increase population and incomes. Prince George's County's community planning staff have conducted studies to evaluate future demands for rail. The studies identified the existing conditions, site access enhancements for pedestrian and bicyclists, the bus facility station, parking demand, ridership projections, and capacity deficiencies (WMATA, 2012).

Status

- Completion of preliminary streetscape design in 2012
- Construction funding to be determined

State Assistance

- MDOT-initiated streetscape project
- Naylor Road station access
- Improvement study completed in 2011

Unique Features

- County committed $340,000 to Branch Avenue "In Bloom" initiative, which encourages economic development

**New Carrollton Metro/MARC/Amtrak (Prince George's County)**

Metro and the state of Maryland are planning to develop, design, finance, and construct a 39-acre, transit-oriented development around the New Carrollton Metro station. The development could potentially contain 2.5 million square feet of office and retail space and 3,000 residential units. This area currently has the best multi-modal transit infrastructure in the Washington, D.C., area.

Prince George's County's general plan focuses on the creation of centers to attract businesses, institutions, and commercial districts (MDOT, 2004). A challenge for developing this TOD included establishing a clear vision of what this place may look like. Many ideas were considered and alternatives were initiated during the study. The concept element was based on three components: neighborhoods (pedestrian-friendly environment), environment (providing open spaces, recreation, parks, habitat and wildlife), and transportation (streets that organize community) (MDOT, 2004). The implementation will consist of three phases: roll out (marketing and outreach), planning (strategy completion), and implementation (identify and build the project and parking strategy). A preliminary financial feasibility analysis that addressed financial returns based on the public and private investments was also created. The projected cost is $2.9 billion, with revenue being generated from the county, new development, and taxes (MDOT, 2004).

Status
- Development team selected, with WMATA, MDOT, and the county collaborating to create the TOD plan
- Transit facilities plan underway

State Assistance
- Inclusion of state land
- $350,000 pre-development assistance
- State offices (Department of Housing and Community Development, DHCD) to be located in the area

Unique Features
- Terminus station for the future Purple Line
- A private site will house DHCD in the mixed-use project

**Wheaton Metro (Montgomery County)**

The Saul Company, county government, Metro, and other stakeholders are involved in Wheaton's current TOD project. The county has developed the Wheaton Redevelopment Program, which is geared towards getting private reinvestments by targeting public investments. WMATA and the Maryland-National Capital Park and Planning Commission incorporated a request for qualifications (RFQ) for private and public partnership for the TOD (Department of General Services, 2012). A private real estate developer partner will be chosen to complete the project.

Status

- The county and WMATA selected a development team to plan and develop a TOD on 8.2 acres of WMATA- and county-owned property.
- The developer (LCOR, Inc.) is working on a development plan through a participatory process.

State Assistance

- MDOT provided about $200,000 in pre-development assistance, including market and fiscal impact studies.

Unique Features

- The county established the Wheaton Redevelopment Program to leverage county resources in the area's transformation.
- Within an enterprise zone

**Shady Grove Metro (Montgomery County)**

The Shady Grove Transit Plan aims to revitalize the current single-use, isolated development, which is primarily single-family, residences, strip retail, and government offices. The plan aims to enhance the environment with well-connected streetscapes and to include residential, commercial, retail, hotels, and other land uses in the area.

Status

- The county is planning redevelopment of 90 acres adjacent to the Metro station.
- Preliminary plans were presented in 2011.

State Assistance

- Screened state-owned property to support the county relocations

Unique Features

- 2006 Shady Grove Sector
- Plan envisions a "lively, mixed-use community"

**Twinbrook Metro (Prince George's County)**

The Twinbrook project is the first TOD project on a metro site in Prince George's County. The project is considered by the Washington Smart Growth Alliance as a smart growth project (City of Rockville, 2012). Phase 1, the residential and retail development, has been completed and is operational.

Status

- Phase 1completed and occupied
- Phase 2 (offices and student housing) started in July, 2011.

State Assistance

- The state provided technical support for market analysis.

Unique Features

- LEED-ND certified
- 2011 "Smart, Green and Growing" Award

**Aberdeen MARC/Amtrak (Harford County)**

Aberdeen is constructing development around its MARC station. It is currently in the planning phase to find areas that need renovation. Some of the tasks include acquiring land for construction and obtaining private-public partnerships (Cahall, 2011).

Status

- The TOD master plan details land-use and implementation strategies for the station area.
- A preliminary engineering study of the station area is underway

State Assistance

- MDOT support for transit needs, market study, and technical assistance for Aberdeen TOD Master Plan

Unique Features

- BRAC revitalization and incentive zone

**Odenton MARC (Anne Arundel County)**

Odenton-area planning for the MARC station consists of reconfiguring roads, pedestrian and bike pathways, block design, streetscapes, and other functions (MDOT, 2008). MDOT, Maryland Transit Administration (MTA), State Highway Administration (SHA), Arundel County officials, and Place Making Group of Parsons Brinckerhoff have collaborated to control station-area planning (MDOT, 2008). The partners broke the planning process into two phases. Phase 1will involve interviewing stakeholders (so they will have an opportunity to express concerns for the development), comparing the Odenton development to previous TOD studies, collecting designs for the TOD framework, and preparing a project notebook that establishes background information and target materials from each agency's visioning and workshop meetings (MDOT, 2008). Phase 2 consists of workshops and meetings with stakeholders, agencies, developers, development team, and state team to discuss the current work and to help future implementation (MDOT, 2008). These two phases will be critical for the Odenton station's goals of creating an environment where people can shop, work, learn, and access transit. Current challenges include the site's semi-rural area, informal building alignments, and the lack of historical pattern to establish successful, new development (MDOT, 2008).

Status

- Pre-development work is underway.
- Project is contingent on the county's infrastructure upgrades.

State Assistance

- MDOT to sell or lease 25 acres to the developer

Unique Features

- BRAC revitalization and incentive zone
- County considering TIF to finance infrastructure

**State Center Metro/Light Rail (Baltimore City)**

State Center is a private-public partnership (P3) project that redefines the urban community. It is a multi-use, transit-oriented program that includes a new class of sustainable residences, office and commercial spaces, and dynamic, street-level retail and restaurant opportunities. A Metro station and light rail station are located in the site.

Status

- 2009 agreement between the state, the city, and the developer to develop a $1.4 billion mixed-use, mixed-income project
- December 2011 lawsuit delayed Phase 1

State Assistance

- 25 acres of state-owned land
- State contribution to garage
- State agencies to lease office space

Unique Features

- Redevelopment of the largest state office complex
- 2010 Congress for New Urbanism Charter Award

**Laurel MARC (Prince George's County)**

The Laurel MARC station's current parking lot is planned to be renovated and turned into a commuter-focused TOD (MDOT, 2009; MTA, 2010). Several studies have examined travel demand for future developments in Laurel Park, Laurel Park Station, and the Laurel TOD. Some of the forecasting methods used background growth rates, trip generation rates for morning and evening peak hour and annual daily traffic volumes, mode choice and transit summary, and peak hour distribution of traffic. The studies concluded that significant renovations are needed to handle the potential traffic increase.

Status

- Developer selected in 2009

- Master developer agreement under negotiation

State Assistance

- Pre-development support
- MTA to sell or lease 4 acres of land

Unique Features

- City considering the use of TIF to support garage and infrastructure costs

**Owings Mills Town Center Metro (Baltimore County)**

The Owings Mills TOD is described as a "Commuter Town Center" by the MDOT Office of Real Estate (MDOT, 2009). Owings Mills is classified as a TOD by the transit system that surrounds its central business district with different mixes of land use. The latest project focuses on the Owings Mills Metro Centre, which will house a parking structure, office spaces, library, and Baltimore Community College (David S. Brown Enterprises, 2012). Planning around the station includes land uses that will attract more people to the area. The state and county will provide funding for the infrastructure (Pash, 2011). Partners for the implementation for this project include MTA, the county, and the private developer (Riderta, 2005). Travel demand forecasts for the Owings Mills area have focused on forecasting future travel behavior for the regional transportation network sites of the Solo Cup Factory (Foundry Row), Owings Mills TOD, and Owings Mills Mall (MDOT, 2012). Forecasting methods included calculations of ITE rates, model rates on trip generation, annual daily traffic, background traffic growth rates, and morning and evening peak hour distribution (MDOT, 2012). The data will help determine improvements and renovations necessary to ensure that commuters choose transit as their primary mode choice.

Status

- Master developer agreement in 2005
- 3,100-space garage completed in 2007
- Public facilities under construction

State Assistance

- MTA is leasing the 43-acre site to the developer.

Unique Features

- Main Street design concept
- County considering use of TIF

**Savage MARC (Howard County)**

Plans include offices, hotels, and residential units so people can take trains, reducing traffic in the Savage Towne Centre. Additionally, since the new developments will be located near Fort

Meade and the National Security Agancy, it will help generate jobs in an area affected by the Federal Base Realignment and Closure (Petrie*,* 2007).
Status
- Master developer agreement approved in 2008

State Assistance
- Sale of 10 acres of state land for TOD

Unique Features
- TIF ordinance to support construction of garage

**Reisterstown Plaza Metro (Baltimore City)**

The Reisterstown Plaza TOD is planned to bring economic development and residential living to the area. The TOD will be located in a low-density area.

Status
- Construction for the General Service Administration (GSA) portion initiated in February 2012
- Remainder of the lot (24 acres) to be developed in the future

State Assistance
- MDOT sold 11.3 acres of state property for the project.

Unique Features
- New 538,000-square-foot facility for Social Security Administration employees

**Westport Light Rail (Baltimore City)**

Westport is developing a green community under the U.S. Green Building Council's new Leadership in Energy and Environmental Design (LEED) for Neighborhood Development program (Westport Waterfront TOD Tiger Application, 2010). This project consists of funding for infrastructure improvements and is intended to stimulate economic growth and lower vehicle miles traveled (VMT) and travel costs. Phase 1 develops residences, offices, and retail space. Phase 2 incorporates a long-term development plan for the Middle Branch Corridor, which includes a green environment with restoration of wetlands and urban parks (Westport Waterfront TOD Tiger Application, 2010). Creating a green TOD will reduce CO2 emissions due to reduced VMT. Besides creating a green environment, the development will create jobs and stimulate the economy. Five international companies have moved 2,200 jobs to the area (Westport Waterfront TOD Tiger Application, 2010).

Status
- Construction of public improvements began in 2010
- Planning for station improvements and pedestrian bridge

State Assistance

- Secured $620,500 in federal funds (2009) to reconstruct the shoreline
- MDOT support for streetscape improvements

Unique Features

- 50-acre, mixed-use, and mixed-income project
- Designated a BRAC zone in 2008

**White Flint (Montgomery County)**

In 2012, the Maryland Sustainable Growth Award for White Flint implementation strategies was accepted by all stakeholders (planners, county officials, and the White Flint partnership). The plan consists of creating a high-density, mixed-use development along Rockville Pike closest to Metro, creating new parks and open spaces, changing Rockville Pike into a boulevard with improved crosswalks, incorporating a grid of new public streets in the transportation network, improving the pedestrian and bicycle environment, and adding rapid bus lanes. The White Flint Sector Plan updates the 1992 North Bethesda Garrett Park Master Plan, with the first phase breaking ground in summer 2012 (Montgomery Co., 2013). It is predicted that the existing transit ridership, biking, and walking will be doubled after the plan's implementation.

Status

- Approved in October 2012

State Assistance

- 3.7 acres of excess State Highway Administration property will be sold to the Federal Realty Investment Trust
- Strong partnerships among the private sector, local and state governments, and community
- Specific transportation infrastructure improvements financed by the White Flint Special Taxing District (Montgomery County Council, 2010)
- Montgomery County is also appropriating funds to support the plan.

Unique Features

- The project will transform 24 acres of asphalt parking lots and an auto-oriented strip retail center into a sustainable, transit-oriented community.
- 3.4 million square feet of residential, office, and retail development in walking distance to the White Flint Metro Station
- An estimated $1.1 billion in new tax revenues over 30 years

### The Effect of TOD on Transportation Systems

Rapid growth in urbanized areas causes many transportation and land-use challenges for local and regional policy makers. Transit-oriented development can respond to these challenges by supporting transit use and providing needed housing and other forms of development (Lund et al., 2004). Therefore, some researchers have investigated the impacts of TOD on transportation systems in their studies. In this section, some of these studies are introduced and discussed.

In a study done by Lund et al. (2004), a measurement of travel behavior in California TODs was provided. Additionally, the study collected detailed data on site and neighborhood factors that potentially affect the likelihood of transit use and modeled those factors in relationship to individual and project-level travel behaviors. Comparisons were also made to 1990-era data in order to understand how travel behavior changes occur over time, as location decisions and mode choice adjust to the new transit accessibility and growing roadway congestion. This broad data collection effort was intended to facilitate a more comprehensive understanding of travel decisions within TODs and to stimulate further analysis and surveys by local jurisdictions, transit agencies, and regional planning entities.

In terms of changes over time, there was not conclusive evidence that transit mode choice increased among TOD residents in the 1992 to 2003 period. Small increases in transit trips were measured, but they were not large enough to establish a statistically valid difference. Survey results showed that transit use is positively related to length of residency.

Disaggregate modeling of office workers' mode choice indicated that parking policies and employer assistance with transit costs significantly influenced those working in offices near California rail stations to commute by transit. Public policymakers can also encourage transit commuting among rail-oriented office workers by enhancing transit services. Frequency of feeder bus services to stations serving offices as well as comparative travel times by transit were both significant predictors.

According to the Lund et al. (2004) study, since parking supply, pricing policy, and employer worksite policies are key influences on commuter mode choice in TODs, policymakers should consider less parking requirements, shared parking, unbundling parking from rent payments, parking cash-out, and/or parking charges. Zhang et al. (2005) stated that density is inversely related to mode choice for automobile trips and directly related to non-motorized travel. Land-use mix has a relatively weak relationship to driving, vehicle ownership, and distance traveled. Design also matters. The magnitude of the influence ranges from 0.002 to 0.6 in elasticity terms. Some studies have shown that urban densities, traditional neighborhood schemes, and land-use mix have a substantial impact on car ownership and use, while others have shown a marginal impact (Badoe and Miller, 2000).

Dock and Swenson (2003) modeled the effect of change in land use on travel demand by using existing regional travel demand models with three enhancements, concluding that the TOD scenario represents a more efficient pattern of trip making. The first set of enhancements addressed short-distance trip capture and the effects of closer proximity to transit at the transportation analysis zone (TAZ) level by developing a focused subarea model at a scale sensitive to TOD micro-grid patterns. The second set of enhancements addressed changes in travel within a TOD that would be caused by changes in urban form, land use density, and mix of uses. Off-line estimation techniques based on travel elasticities were used to calculate these effects within a single TAZ. The third set of enhancements addressed interaction between a TOD and an adjacent development. A similar set of off-line estimation techniques were used for adjacent TAZs.

Dock and Swenson (2003) discussed that current regional models need to be modified to consider TODs and their characteristics and development pattern or TODs need to be modeled separately. Lund et al. (2004) studied the travel characteristics of residents before and after TODs were developed. The study was based on the data collection and comparison with previous records.

Transit mode share is an important parameter for the success of a TOD. Hendricks (2005) argued that if there is poor transit service, the land-use qualities will never influence a shift of mode share to transit. Some people will live and work in a TOD, but some people may not like to live near their place of work; thus, they may travel to work. Many studies have observed that the mode shares of non-work trips significantly shifted towards walking, cycling, and transit with TOD (Cervero and Radisch, 1996; Rajamani et al., 2003). Zhang (2005) found that, when the accessibility was changed, the travel time and trip frequency also changed for non-work travel in a TOD. Meanwhile, Messenger and Edwing (1996) found that for work trips, the bus mode share by place of work was related to the cost of parking, transit access to downtown, and overall density.

Chatman (2003) studied the influence of workplace employment density and share of retail employment on vehicle miles traveled (VMT) to access personal commercial activities, employing a joint logit-Tobit model. The study was based on the hypothesis that a high density of shops and services near the workplace may make it easier to carry out personal commercial activities via foot or transit before, during, or after the work day. However, the study concluded that the availability of retail at the workplace is not significantly related to mileage traveled, but employment density at the workplace is strongly associated with a slightly lower likelihood of car commuting and reduced personal commercial VMT.

Schlossberg and Brown (2004) developed 12 measures based on Geographic Information System (GIS) to visualize and quantify pedestrian environments at various TOD sites; these measures were useful for planning a TOD.

Studies regarding the measurable impacts of land-use characteristics on transit use and access mode to transit have verified that high levels of land-use mix at the trip origins and destinations yield an increase in transit shares and non-auto commuting (Cervero and Radisch, 1996; Cervero and Duncan, 2006; Holtzclaw, 1994; Krizek, 2003).

A second group of studies focused on the impacts of land use on transit mode shares. In an analysis of 57 suburban activity centers across the United States, Cervero (1989) noted that every 10 percent increase in floor space of retail and commercial uses was associated with a 3 percent increase in transit shares. Although centers had comparable employment levels, no socio-economic control variables were introduced in the models produced. Complementing this finding, a 1994 Cambridge Systematic study, which characterized the employment centers in Los Angeles using a composite land-use mix variable, concluded that transit share increased substantially with higher land-use mixing within a quarter mile of the sites. Kockelman (1997) utilized the 1990 San Francisco Bay Area Travel Survey to conclude that land-use balance and mix had more impact on mode choice and VMT per household than socio-demographic characteristics. In a more recent study, using trip records for Montgomery County residents from the 1994 Household Travel Survey, Cervero (2002) developed binomial and multinomial models to analyze the link between the built environment and mode choice. Transit mode shares were found to be most sensitive to land-use diversity.

**The Effect of TOD on Travel Behavior**

There are quite a few studies in the body of literature focused on the effect of TOD on overall and mode-specific trip generation. However, in most of these studies, the effect of the socio-economic characteristics of residents has not been controlled in the modeling process. Most of these studies only calculated the vehicle trip rate in TOD-designated areas and then compared them with that in non-TOD areas using loop detectors or pneumatic tubes along with means. Colman et al. (1992) investigated the impact of TODs on travel behavior and proposed several different trip generation rates. The study modeled trip generation rates in TOD zones of Sacramento County using the change in vehicle ownership due to improvement in transit service and urban structure. Results of this study showed that TODs can reduce motorized trip generation by 6 to 7 percent compared to an auto-oriented suburban development.

Lapham (2001) calculated the trip generation rate for eight TODs in the Portland metropolitan region and developed several regression models of the relationship between trip generation rate and TOD attributes such as residential density and rental price. The results showed that the average trip generation rates in TOD areas are well below the proposed Institute for Transportation Engineers (ITE) trip generation rates.

Arrington and Cervero (2008) modeled vehicle trips per hour for 17 TOD sites in Philadelphia, Portland, Washington, D.C., and the East Bay area (in California). The results showed that these TOD zones had about 44 percent lower vehicle trip rates during a typical weekday, 48 percent lower rates during the PM peak, and 49 percent lower rates during the AM peak than the ITE rates.

The metropolitan transportation commission of the San Francisco Bay Area (2006) calculated the vehicle trip reduction factors and the transit increase factors by transit operator/mode (BART, a rapid rail; Caltrain, a commuter rail; SF Muni, Light rail; and VTA, Light Rail) in a quarter-mile and half-a-mile band of these transit operators based on the 2000 Bay Area Travel Survey. The results showed that when compared to the region vehicle trip rate, TOD residents living around BART or Muni LRT stations made 50 percent fewer vehicle trips.

# METHODOLOGY

## TOD Definition

As discussed earlier, there have been several different definitions for TOD proposed by planners, researchers, and practitioners. However, there are no clear paths or generally accepted definitions and standards to follow both in terms of the theoretical and practical aspects of TOD. In theory, TOD neighborhoods often consist of a center, with a major public transit station, surrounded by high-density development with a mixture of residential, employment, shopping, and civic uses and gradually lower-density development spreading outward from the center. In practice, many TOD studies defined its boundaries using a half-mile buffer around selected transit stops.

The research team formalized a quantitative methodology to identify TOD areas. It comprehensively considers all of the generally accepted theoretical aspects of TOD, such as the presence of one or more transit centers surrounded by high residential and employment densities and mixed-use development.

The proposed methodology contains four main factors:

1. walkability and high density
2. walking distance to a transit station
3. collaboration of mixed uses and transit
4. affordable housing availability around transit

The research team uses the Traffic Analysis Zone (TAZ) system defined by Metropolitan Washington Council of Governments (MWCOG) and Baltimore Metropolitan Council (BMC) and identifies a TAZ as a TOD if it meets the following conditions:

$$TAZ \in TOD\ iff \tag{1}$$

$$\left(D_R^{TAZ} \geq D_R^{Avg}\ OR\ D_E^{TAZ} \geq D_E^{Avg}\right)$$

$$B_{TAZ} \leq B_{Avg}$$

$$Rank_{TAZ}^{Entropy}/n \geq 0.30$$

$$X_{HT} \leq 0.45$$

$$TAZ \in U_{1 \leq i \leq n} Ball_{0.5}^{T_i}$$

where,

$D_R^{TAZ}$= Residential density of TAZ= $residential\ population/area\ (acre)$
$D_E^{TAZ}$= Employment density of TAZ= $employment\ population/area\ (acre)$
$D_R^{Avg}$= Average residential density for the entire metropolitan area
$D_E^{Avg}$= Average employment density for the entire metropolitan area
$B_{TAZ}$ = Average block size for each TAZ, sq. mile
$B_{Avg}$ = Average block size for the entire metropolitan area, sq. mile
$X_{HT}$ = Housing & transportation affordability; % of housing + transportation cost of households' income

$Rank_{TAZ}^{Entropy}$ = The rank of Entropy (TAZ) when sorted decreasingly according to entropy
$Ball_R^C$= The circle of radius r (mile) around point C
$T_i \ (1 \leq i \leq n)$= The point where the transit station is located

and

$$\text{Entropy} = -\sum_j \frac{P_j ln\,(P_j)}{ln(J)}$$

where $P_j$ is the proportion of land use in the $j^{th}$ use category, and J is the number of different land use type classes in the area[1].

This methodology is applied in both the Washington, D.C., and Baltimore metropolitan areas separately. The result is in the model as a binary variable called TOD. Value 1 for this variable shows that the TAZ is considered a TOD zone, while value 0 shows that the TAZ is a non-TOD zone.

However, the methodology presented above is an arbitrary method that has been chosen based on the research team's knowledge, experience, and data availability. Various other definitions and quantitative methods can be applied in the future to test the sensitivity of the results against those other types of methodologies and definitions for TOD.

The 2007/2008 household travel survey (HTS) data was utilized to analyze travel behavior differences between households who live in TOD areas and the ones who live outside TOD areas. Then, the research team performed descriptive and statistical analyses to study the households' travel characteristics.

## The Effect of TOD on Transportation Models

In a test environment, the research team modified the trip generation step of the Maryland Statewide Transportation Model (MSTM) to incorporate the effect of TOD on a transportation system.

MSTM is a statewide transportation model that works at a regional, statewide, and urban level. The regional model covers North America; the statewide model includes Maryland, Washington, D.C., Delaware, and selected areas in Pennsylvania, Virginia, and West Virginia; and the urban model connects the statewide model to the existing urban models. For example, it links the Baltimore Metropolitan Council (BMC) and Metropolitan Washington Council of Governments (MWCOG) models. MSTM uses a statewide model level zone (SMZ) rather than a traffic analysis zone (TAZ). There are 1,602 SMZs in the model, 1,473 of which were reused in the study area.

In the original MSTM, each SMZ is categorized as one of nine area types using activity and density, regardless whether it is a TOD. The trip production component of trip generation in the

[1] The entropy formula and definition is directly borrowed from Zhang et al. (2011).

MSTM model is a cross-classification model for six trip purposes and three regions. The trip purposes are home-based work (HBW), home-based shop (HBS), home-based school (HBSh), home-based other (HBO), non-home-based work (NHBW), and non-home-based other (NHBO).The three regions are urban, suburban, and rural. The work-related trips are cross-classified by income and number of workers, while non-work trips are cross-classified by income and household size. The trip attraction is a regression model applied to SMZ socio-economic variables (MSTM User Guide, 2010).

The research team used an approach similar to MSTM to categorize SMZs as one of three area types (rural, suburban, and urban) rather than nine area types, and then separated them as being TOD or non-TOD and made five area types/TOD categories that will be explained later. The approach is as follows.

$$\text{Activity (A)} = \text{Households} + \text{Total Employment} + \text{Retail Employment}$$

$$\text{Activity Density (AD)} = A / \text{Area}$$

The research team sorted and broke down the 1,473 SMZs into three groups based on activity density (AD). Table 1 presents the categories, number of SMZs, and percentages in each category. The nine rural TODs were combined with the suburban TODs since there are no rural TODs in the real world. As presented in table 2, each SMZ is allocated within one of the five defined area types/TOD. Out of the 14,363 households in the HTS, 1,867 are located in a TOD area and 12,496 are located in a non-TOD area.

After introducing new regions (the five Area Type/TOD), the research team performed a cross-classification for each trip purpose and each region. A regression model was also developed by the research team for the trip productions. Since the trip attraction model is based on socio-economic data for each SMZ, which is not changed by TOD determination, the research team kept the trip attraction model unchanged.

**Table 1. SMZ Distribution by Area Type and TOD.**

| | Urban | Suburban | Rural |
|---|---|---|---|
| **TOD** | 77 | 21 | 9 |
| | 5.2% | 1.4% | 0.6% |
| **Non-TOD** | 205 | 399 | 762 |
| | 14% | 27% | 52% |

**Table 2. The Five Area Types/TOD Codes.**

| Area Type/TOD | Code |
|---|---|
| **Rural Non-TOD** | 1 |
| **Suburban Non-TOD** | 2 |
| **Urban Non-TOD** | 3 |
| **Rural/Suburban TOD** | 4 |
| **Urban TOD** | 5 |

### Data Collection

In the analysis of the impact of living and traveling within and to TODs on various aspects of travel behavior, the research team employed multiple data sources and then used these various datasets in the analyses in order to separate the effect of the policy variable and the other influencing factors (e.g., socio-demographic characteristics, fuel price, and supply-side variables). In this section, the data sources and the variables included are introduced and explained in details.

### Household Travel Survey Data

The 2007/2008 Household Travel Survey (HTS) data for Washington, D.C., and Baltimore was obtained from the MWCOG and involved 14,000 households (about 31,000 persons) in the Washington, D.C., region and adjacent areas, who were randomly selected to record travel diaries for two consecutive days (workdays not weekends). As the main data source for our VMT, trip generation, and mode share analysis, this dataset includes four major sections of household, person, vehicle, and trip information, each of which provide information regarding household and personal socioeconomic and demographic characteristics (household size, income, car ownership, number of children, etc.), vehicle information (e.g., vehicle make and model, fuel consumption, etc.), activities, and travel information (e.g., travel distance, mode, travel time, purpose of the trip, and origin/ destination information) for each surveyed household in the metro area. Each household’s home location is geocoded at the TAZ level.

After data processing and deleting the observations with missing data, our dataset consists of nearly 8,000 households in the Washington, D.C., metro area, and 4,000 households in Baltimore metro area.

The data included information on residence jurisdiction of each household, residence census tract, residence TAZ, housing type, housing tenure, household size, number of students in the household, number of licensed drivers in the household, number of workers in the household, number of disabled people in the household, number of vehicles available, number of bicycles available, household’s income, etc. It also provided information such as age, gender, race, driver status, relationship to the household respondent, driver’s license possession, personal disability status, work status, type of employment, number of jobs the person has, hours the person worked in the last week, work location of the person (home, office, etc.), work place (city, county, and state), usual travel means to work last week (drive alone, carpool, transit, taxi, walk/bike, etc.), primary job start/end time and work days, and work schedule for each member of the household 18 years and older. There was also some information on bike use and bike facilities available, such as whether a secure bike facility was available at work, number of weekdays a bicycle was used, type of bikeway mostly used. If the respondent was a student, they were asked if a secure bicycle facility is available at school, usual travel means to school (drive alone, carpool, transit, taxi, walk/bike, school bus, etc.), and days of school attended in the last week.

Finally, the trip data file included some information about daily trips, such as origin/destination trip purpose (home, work, school, shop, etc.) and activity, origin/destination jurisdiction (FIPS code) and address, origin/destination zone, trip start time, trip end time, primary travel mode (transit, auto, walk, bike, taxi, light rail, etc.), mode used to access transit, mode used immediately after transit, origin/destination vehicle occupancy, reported travel time (in minutes), estimated trip distance (miles), travel party composition, and socioeconomics of all household members.

The VMT and trip generation analysis were both at the household level. In order to calculate the households' VMT, the research team added the trip distance of each trip made by each member of the household to obtain the total amount of distance traveled by the entire household. As a result, the VMT used is not annual VMT, but the VMT for the survey period only. For trip generation analysis, all trips made by households living in TOD areas were calculated and used in the model.

The mode share analysis was at the zone level, wherein all trips originating from each zone was counted and the percentage of each mode share in each zone was calculated and used as the dependent variable.

### Geocoded Land Use and Transit Stations Data

To calculate the built environment and land-use characteristics of the neighborhood of residence for each household, the 2005 Washington, D.C., and Baltimore land-use data were used. These datasets included population and employment information, by type, in each TAZ. The land-use variables used include residential and employment densities, mixed-use development (entropy), and distance to the central business district (CBD). These land-use variables and their calculation methods have been summarized in table 3. They were calculated using the ArcGIS software package and incorporated into the models along with socioeconomic and demographic information of each surveyed household in the area.

**Table 3. Variable Description and Data Source.**

| Variable | Variable description | Computation |
|---|---|---|
| **Residential Density** | Residential density | persons/acre |
| **Employment Density** | Employment density | jobs/acre |
| **Distance to CBD** | Distance from CBD-mile/accessibility measurement | Straight line from zone centroid to CBD |
| **Entropy** | Level of mixed-use development | Entropy formula |

| | | |
|---|---|---|
| **Block size** | Street connectivity/walkability measurement | Average block size (sq. mile) |

To compute the average block size, the research team used the 2010 census block GIS shapefiles from a Census Tiger dataset provided by the U.S. Census Bureau. The ArcGIS software was used to calculate the area of each census block in each TAZ and then they were averaged to obtain the single variable, called average block size, for each TAZ.

### Housing and Transportation Cost Data

In order to investigate the availability of affordable housing in TOD zones as part of the proposed TOD definition, the research team used the location affordability index (LAI) dataset, which includes a housing and transportation cost index (also known as location affordability index) as a percentage of a household's annual income. The dataset is developed by the U.S. Department of Housing and Urban Development (HUD) at the census block group level. The research team downloaded the data for two metropolitan areas of Washington, D.C., and Baltimore at the block group level and then aggregated the data to the TAZ level. The research team defined housing affordability based on the combined housing and transportation cost as percentage of households' annual income. If the housing and transportation cost of a particular household was lower than 45 percent of its annual income, we call it affordable and this factor has been considered as a requirement for TOD identification framework used in this study.

This dataset provides housing and transportation costs for different types of households, such as regional typical, low, moderate, and high income households; single or dual-income households; retiree households, etc. In the calculation procedure of the index, several factors have been considered, such as households' income, commuting pattern, vehicle ownership, and VMT as well as the built environment and transit accessibility of the households' neighborhood of residence.

### Modeling Approach

### Multi-level, Mixed Effect Regression Model- VMT

For modeling the travel behavior within TOD and non-TOD areas, the multi-level, mixed effect regression modeling approach has been taken. This approach contains both fixed and random effects coefficients and could be viewed as a generalization of the variance component and regression analysis models. This model allows us to have different coefficients by subject groups. Subjects in the same level/group are likely to be similar to each other in terms of their observable characteristics, meaning households living in the same TAZ (whether or not it is a TOD) tend to have a similar travel pattern and this model is able to capture these similarities and their magnitude.

The mixed model can be represented as:

$$y = X\beta + Zu + \varepsilon$$

Where:

- y is a vector of observations, with mean $E(y) = X\beta$

- β is a vector of fixed effects
- u is a vector of independent identically distributed random effects with mean E(u) = 0 and variance-covariance matrix var(u )=G
- ε is a vector of random error terms with mean E(ε) = 0 and variance var(ε)=R
- X and Z are matrices of regressors relating the observations y to β and u

The research team considered the effect of socio-demographic factors and some selected land-use characteristics as a fixed effect. Also, living in a particular TAZ was considered a random effect, since both the households in the survey and the TAZs are randomly selected from the entire population of households living in the same TAZ and all the TAZs in the whole metro area. The above justification lies in the fact that the errors of samples within each TAZ are likely correlated.

### Trip Generation and Trip Distribution/Length Model

The trip generation model is the first step of the classical, four-step transportation demand forecasting process. Trip generation aims at predicting the total number of trips generated by households. This analysis can be done at the household level or zonal level. For the analysis, the research team used multiple regression models at the household level in order to separate the effect of household socio-economic characteristics from the effect of TOD on the travel behavior of TOD residents. For the analysis, the research team used the information from the surveyed residents' two-day travel diary. In all statistical analysis steps, trips longer than 50 miles were excluded as they are considered to be long-distance trips[2].

The multiple regression method was used to model trip generation with two sets of predictors: households' characteristics and whether or not household's residence location is TOD. Inclusion of households' characteristics to some extent captures the possible self-selection effect and makes our results more reliable than the past analyses which did not include these factors due to either lack of data or their scope of analysis.

The equation below represents the structure of the research team's trip generation model. The dependent variables include number of auto, non-auto, and total trips. The socio-economic variables included in the models are household size, number of vehicles, households' annual income, number of children, and number of workers in the household.

$$Trips = f(SES_{ij}, TOD_j) \quad (2)$$

Where:

$Trips = number\ of\ trips\ by\ mode$
$SES_{ij} = socioeconomic\ attributes\ of\ HH\ i\ living\ in\ zone\ j$
$TOD_j = dummy\ variable\ indicating\ whether\ zone\ j\ is\ TOD\ or\ not$

[2] According to NHTS 2001

The model specification for the trip length model was similar to that of trip generation, using socio-demographic characteristics of the households and the binary variable representing TOD.

### Mode Share Model

The seemingly unrelated regression (SUR) method was employed to model mode share using three primary modes of auto, transit, and walk/bike. The percent of the mode share of all trips originating from each TAZ was used as the dependent variable, and the independent variables include land use variables and household characteristics. Since the model was at the zone level, all the households' characteristics used have been averaged from individual households to the entire households living in a specific zone (equations 3, 4, and 5).

$$Auto = \alpha_1(SES_j) + \beta_1(BE_j) + \epsilon_1 \quad (3)$$

$$Transit = \alpha_2(SES_j) + \beta_2(BE_j) + \epsilon_2 \quad (4)$$

$$Walk \,\&\, Bike = \alpha_3(SES_j) + \beta_3(BE_j) + \epsilon_3 \quad (5)$$

$$\text{S.t:} \begin{cases} \alpha_1 + \alpha_2 + \alpha_3 = 0 \\ \beta_1 + \beta_2 + \beta_3 = 0 \end{cases}$$

Where:

$Auto = Percent\ of\ auto\ mode\ share\ originating\ from\ zone\ j$

$Transit = Percent\ of\ transit\ mode\ share\ originating\ from\ zone\ j$

$Walk\ \&\ Bike = Percent\ of\ walk\ \&\ bike\ mode\ share\ originating\ from\ zone\ j$

$SES_j = Socioeconomic\ attributes\ of\ HH\ \ living\ in\ zone\ j$

$BE_j = Built\ environment\ attributes\ of\ zone\ j\ including\ residential\ density,$
$employment\ density, entropy, and\ TOD\ binary\ variable$

This modeling approach allows us to perform the analysis with a set of simultaneous equations and preset constraints. The main constraint used in our model was that the coefficients for each variable in each row should sum up to zero. This constraint was added to capture the changes in different modes simultaneously. Furthermore, this approach has the capacity to consider different sets of variables for each mode share; thus, more mode-specific variables could be used to model the share of each mode in the future.

Mode share modeling was done in two steps: (1) the research team only controlled for household characteristics, so that the TOD variable captured all the effect of the built environment and transit proximity at the same time, and (2) the research team added land-use variables to the model to distinguish the effect of the built environment apart from other factors in a TOD such as transit proximity.

## RESEARCH FINDINGS AND DISCUSSION

### TOD Determination

First, the research team identified all the major rail transit stations and their half-mile buffer area in both metro areas on the map. In figures 7 and 8, the location of rail stations and the buffer zones are shown in the Washington, D.C. and Baltimore areas.

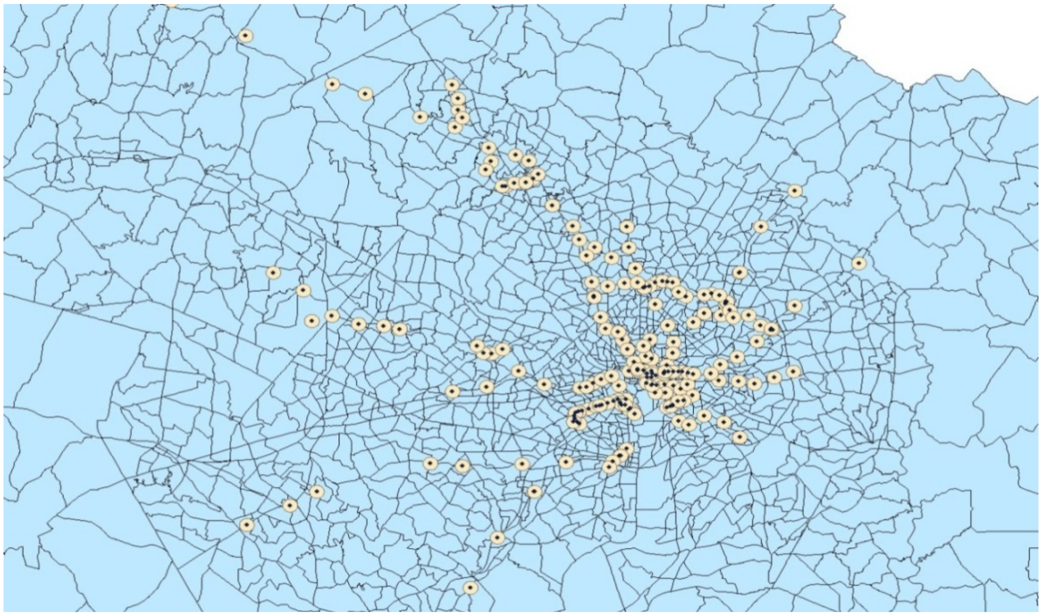


**Figure 7. Rail Transit Stations in the Washington, D.C. Area and Their Half-mile Buffer Zones.**

**Figure 8. Rail Transit Stations in the Baltimore Area and Their Half-mile Buffer Zones.**

In the next step, the research team applied the other criteria to identify the designated TOD zones. Figures 9 and 10 illustrate the TOD zones in Washington, D.C. and Baltimore metropolitan areas (highlighted in red) and their positions with respect to the major arterials highways.

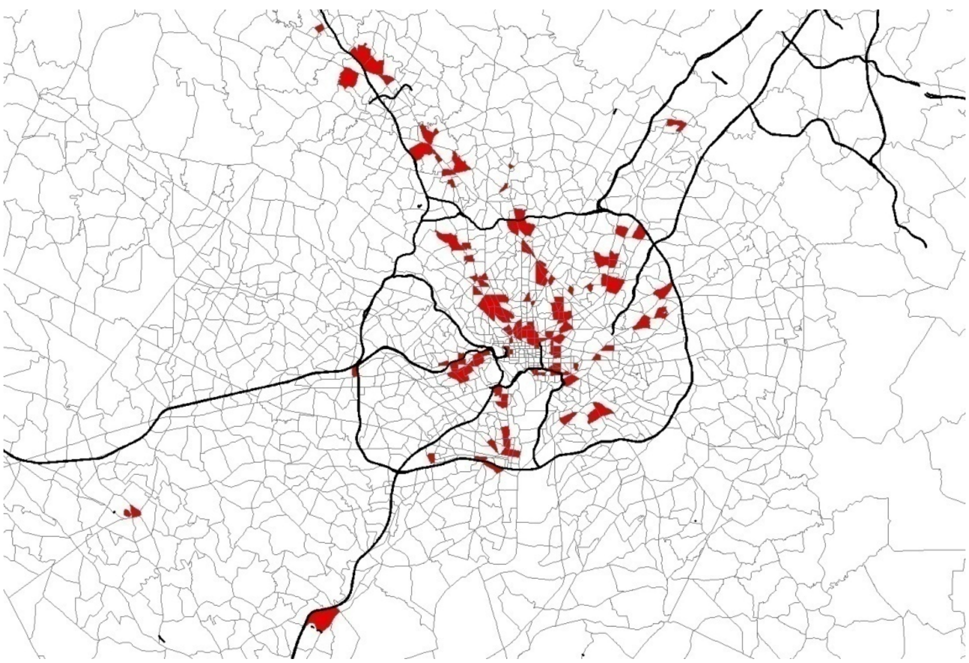


**Figure 9. TOD Zones in the Washington, D.C. Area.**

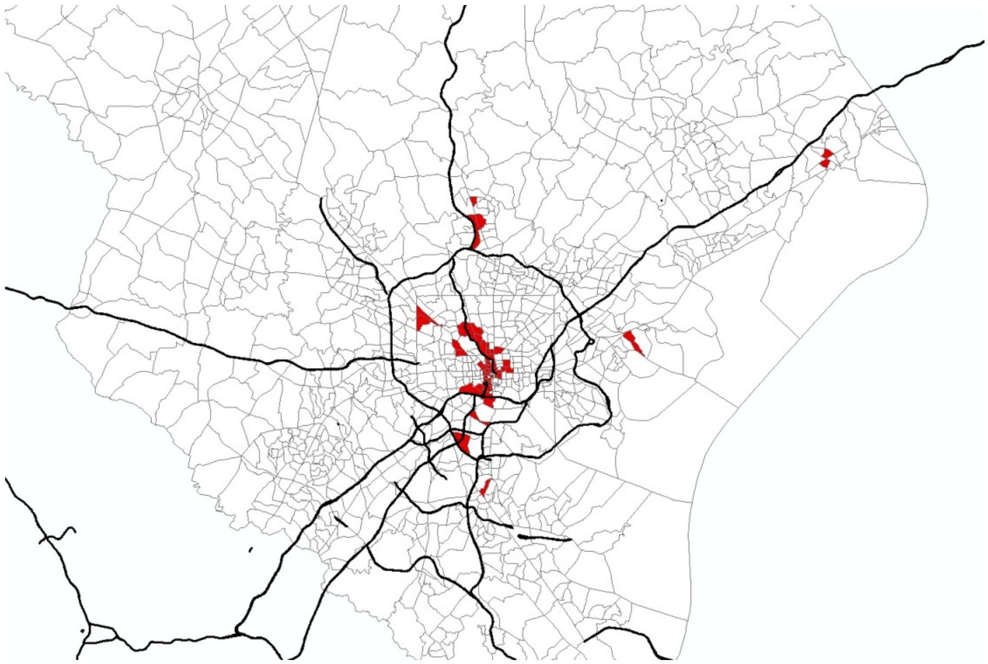


**Figure 10. TOD Zones in the Baltimore Area.**

TOD zones were identified based on the mathematical framework proposed for TOD definition. Then, the residents living in the TOD areas were identified and their social and demographic characteristics, as well as several selected travel behavior indicators, were reviewed and compared to those households living in areas designated as non-TOD.

The research team then adopted SMZ numbering for BMC or MWCOG to be consistent with the MSTM. Thus, a conversion was needed to specify SMZ numbers for each household. MWCOG includes 2,191 TAZs, 91 of which were determined to be TOD. BMC has 1,422 TAZs, including 61 TODs. After converting TAZs to SMZ numbers, the research team specified which SMZs were TOD. As presented in Figure 11, out of 1,473 SMZs, 107 were determined to be TOD.

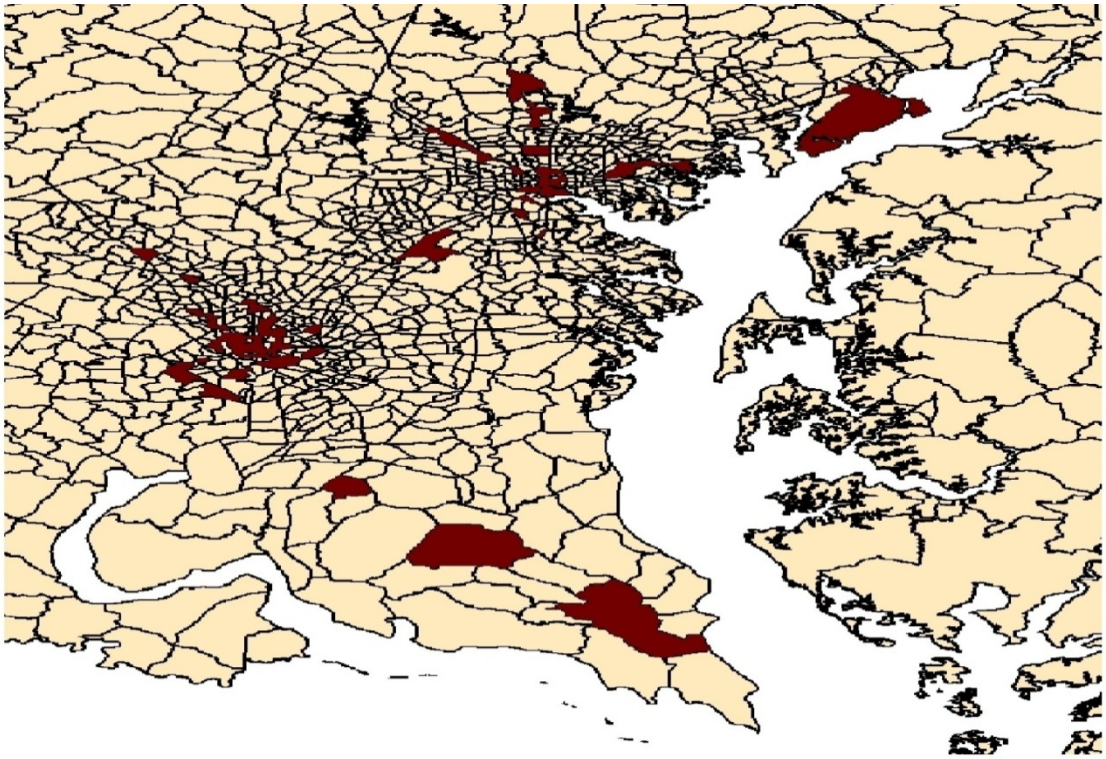


**Figure 11. TODs in Statewide Area.**

The research team then applied the conversions into the HTS household file in order to find the SMZ code for each household and added a variable to show which household lived in a TOD area.

**Descriptive Analysis**

The research team first performed a descriptive analysis to attain general information about the socioeconomic and demographic characteristics of the households in both the Washington, D.C., and Baltimore metropolitan areas to compare households living in TOD and non-TOD areas and better understand and track their travel patterns.

The households' travel characteristics are presented in figures 12 and 13. The results are fairly intuitive. As shown in figure 12, on average, total travel distance (miles) is higher among households living in non-TOD areas than those living in TOD areas. Total auto distance traveled is higher, while total transit distance traveled is lower for households living in a non-TOD than those living in a TOD area.

Figure 12 also shows that, on average, households who live in non-TOD areas spend more time traveling than those living in TOD areas. The auto travel time for households living in non-TODs is higher, while their transit travel time is lower than the households living in TOD areas. Over 50 percent of households living in TOD areas travel less than 20 miles on a daily basis, while households living in non-TOD areas travel longer distances. As presented in figure 13, households living in TOD areas have a smaller size, and lower number of vehicles than those in non-TODs. However, the number of bikes is similar in both households.


**Figure 12. Descriptive Analysis of Household Travel Behavior in TOD and Non-TOD Areas.**

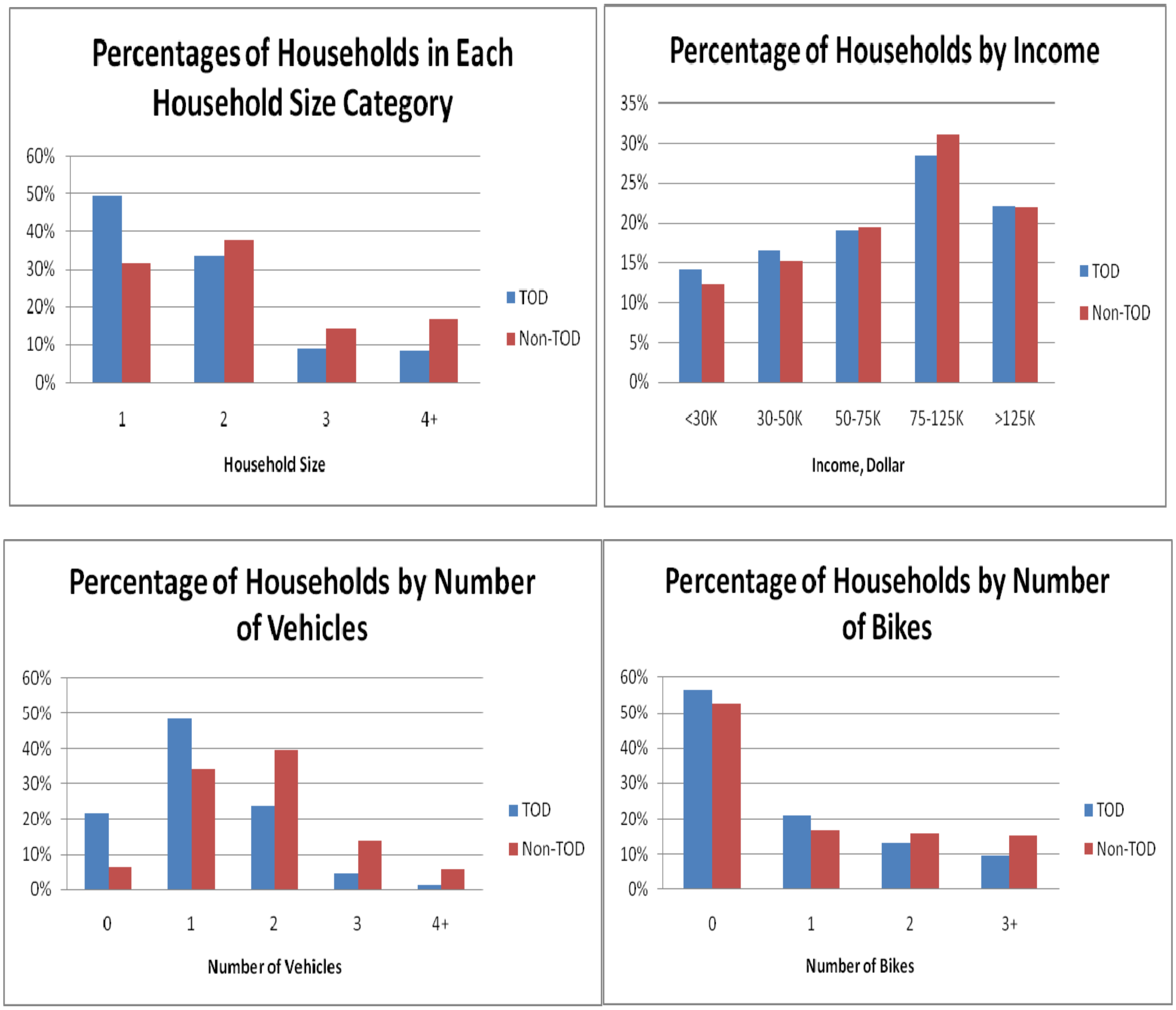



**Figure 13. Descriptive Analysis of Household Characteristics in TOD and Non-TOD Areas.**

To have an image of the age distribution in the study area and in the TOD areas, the research team extracted statistics from the raw data. Of the 31,330 individuals in the HTS data, 3,353 were living in TOD areas and 27,977 were living in non-TOD areas (figure 14). Figure 15 presents the percentage of individuals living in TOD and non-TOD areas by age group. As shown in the figure, the non-TOD areas host more numbers of people for the first three age groups (0-4, 5-15, and 16-18 years old), but the TOD areas have more numbers of young adults in the 25-34 age group. For the remaining age groups, the TOD and non-TOD areas are almost the same.

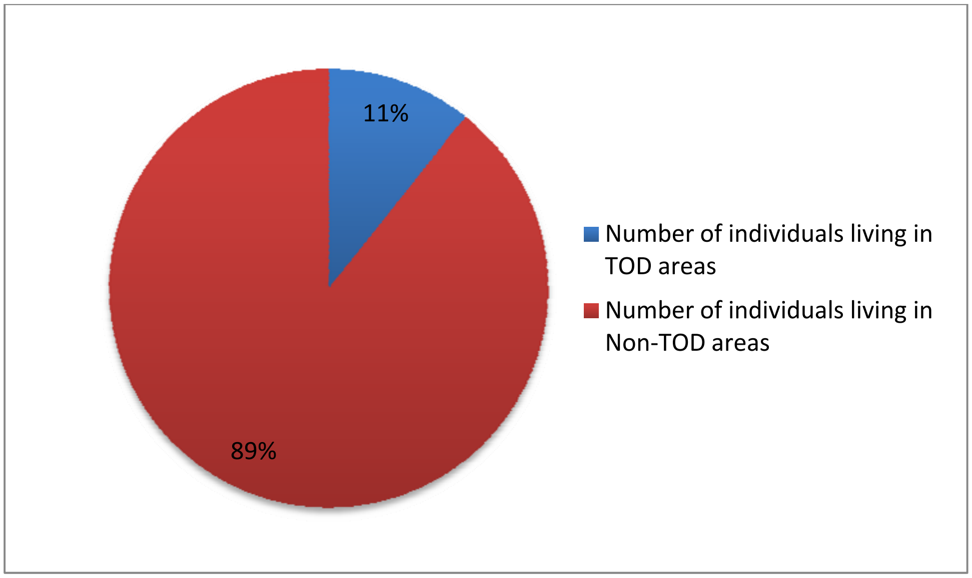



**Figure 14. Percentage of Individuals Living in TOD and Non-TOD Areas.**

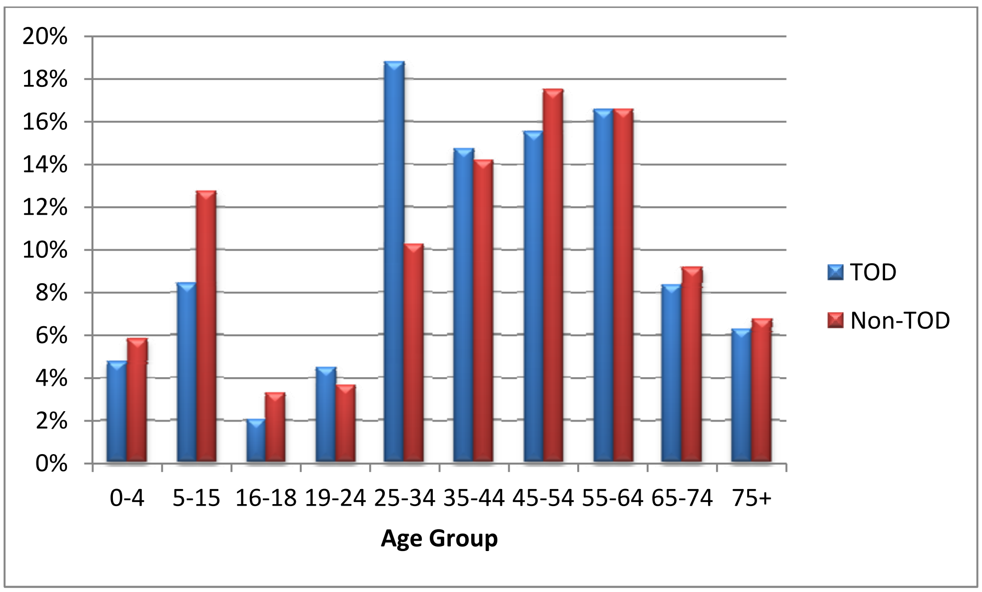



**Figure 15. Percentage of Individuals by Age Group in TOD and Non-TOD Areas.**

The research team analyzed household travel characteristics based on the newly defined TOD area type as presented in figures 16 and 17. On average, total travel distance (miles) was higher among non-TOD residents than TOD residents. Total auto distance traveled was higher and total transit distance traveled was lower for households living in non-TOD areas than those living in TOD areas.

The research team also compared household travel characteristics between Baltimore and Washington, D.C. TOD areas. As presented in figures 18-20, total travel time in Washington, D.C. and Baltimore is almost the same. Households in Baltimore TODs spent more time in automobiles and less time in transit. In Baltimore TODs, households traveled longer distance using automobiles than those in Washington, D.C., while distances traveled by transit were the same in both areas. Washington, D.C. TODs had slightly more single households than Baltimore. A slightly higher percentage of Baltimore TOD households did not own any vehicles. Over 50 percent of Washington, D.C. households own only one vehicle. Washington, D.C. TOD households had higher incomes than those in Baltimore. Households in both areas had a similar number of bikes. People living in Washington, D.C. TODs had almost the same age distribution as the ones in Baltimore.

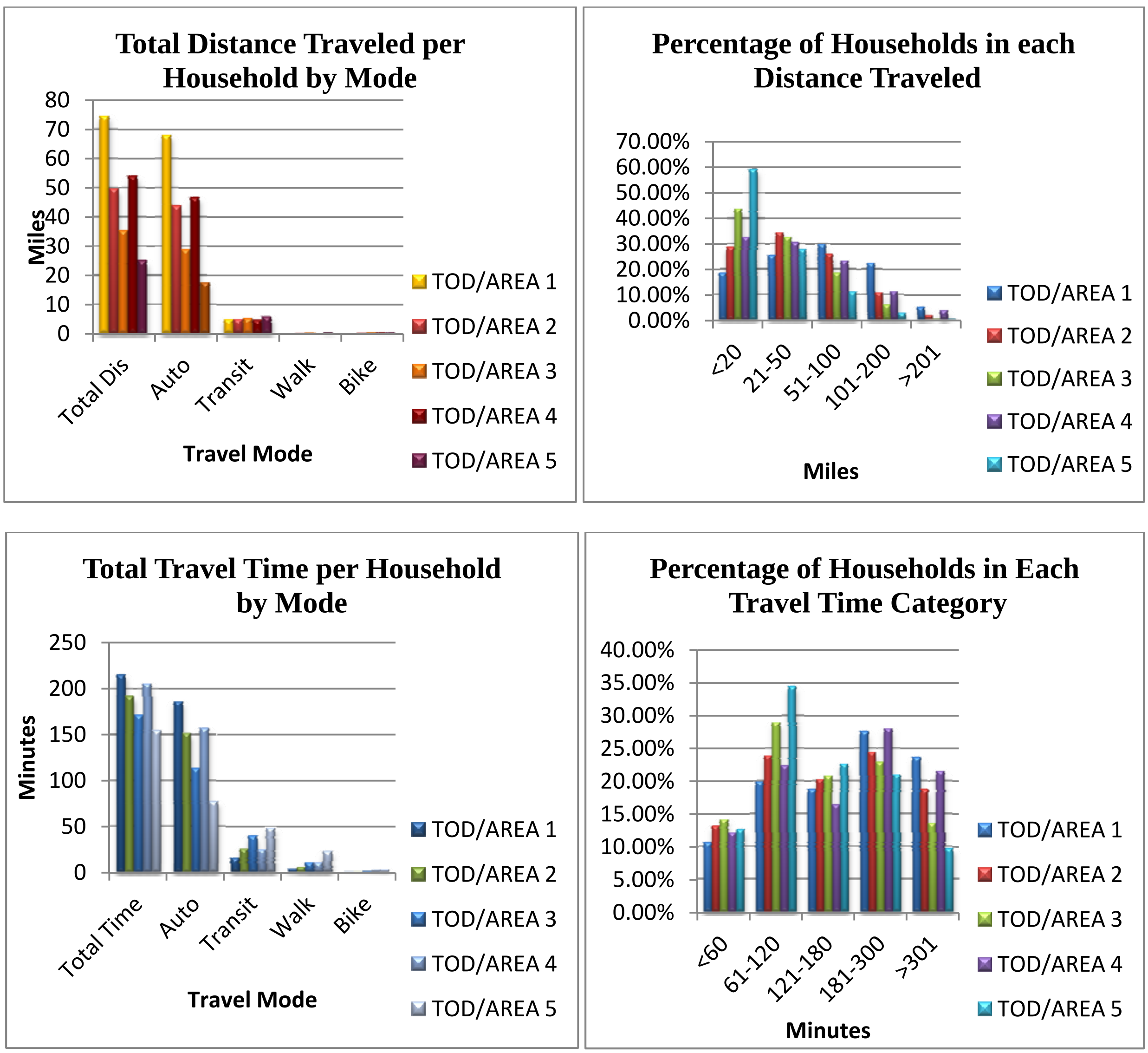



**Figure 16. Household Travel Characteristics in Different TOD/Area Types.**

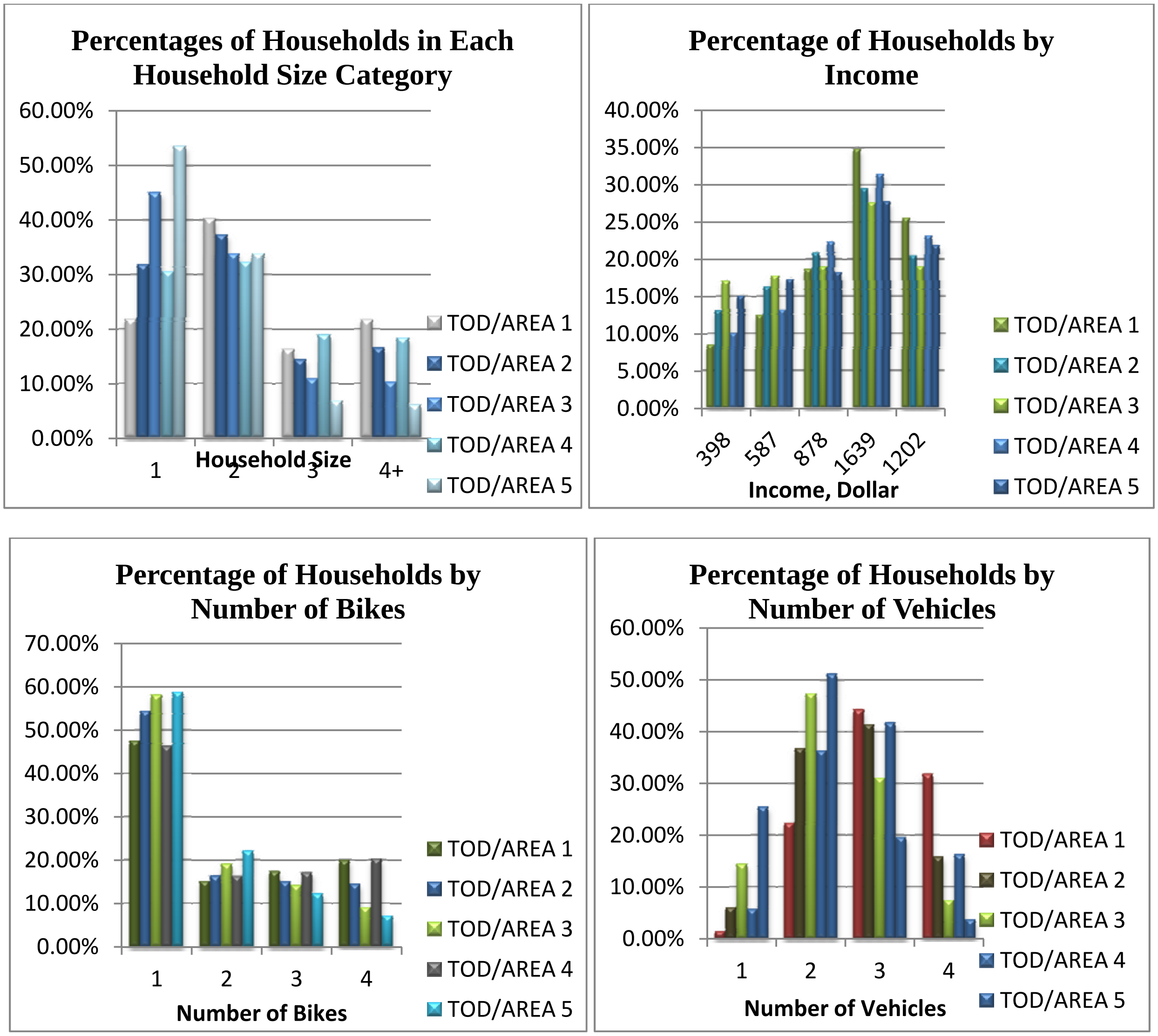



**Figure 17. Household Characteristics in Different TOD/Area Types.**

As presented in figures 18- 21, total travel time and auto travel time per person are higher in the Baltimore area than in the Washington, D.C. area, while transit and walk travel times were lower. Similarly, total distance and auto distance per person were higher in the Baltimore area than in the Washington, D.C. area, while transit, bike, and walk travel times were lower. Individuals living in a TOD area had lower auto travel time than the ones in a non-TOD area, while all other travel times were higher for them. Distance traveled by individuals living in a TOD area was less than the ones in a non-TOD area in all modes but transit. People living in TOD areas in Baltimore have lower income than the ones in DC area. The reason may be that low income families in Baltimore  need The age distribution in Baltimore and Washington, D.C. was similar.

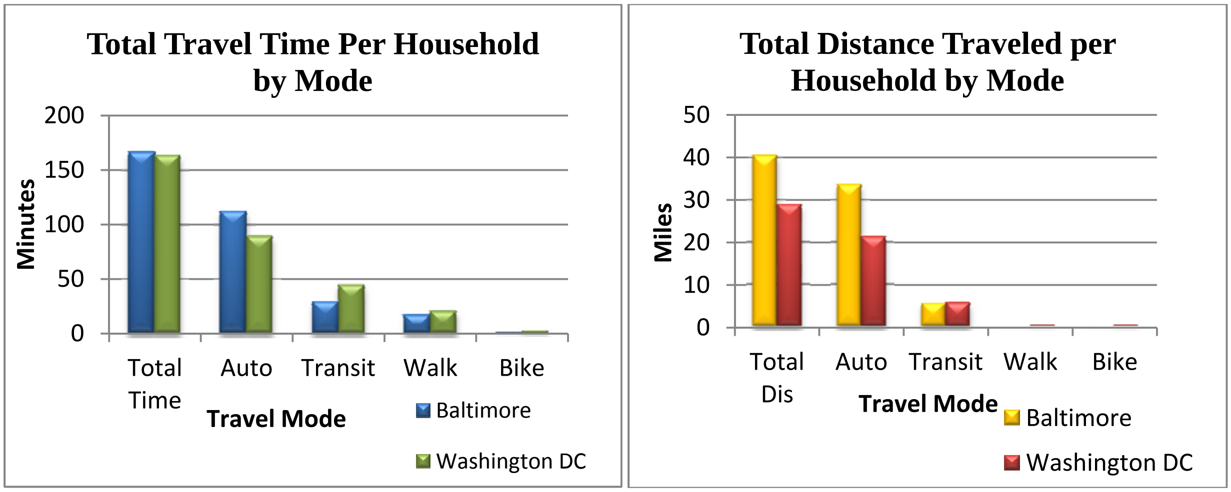



**Figure 18. A Comparison of Household Travel Characteristics in Washington, D.C. and Baltimore TOD Areas.**

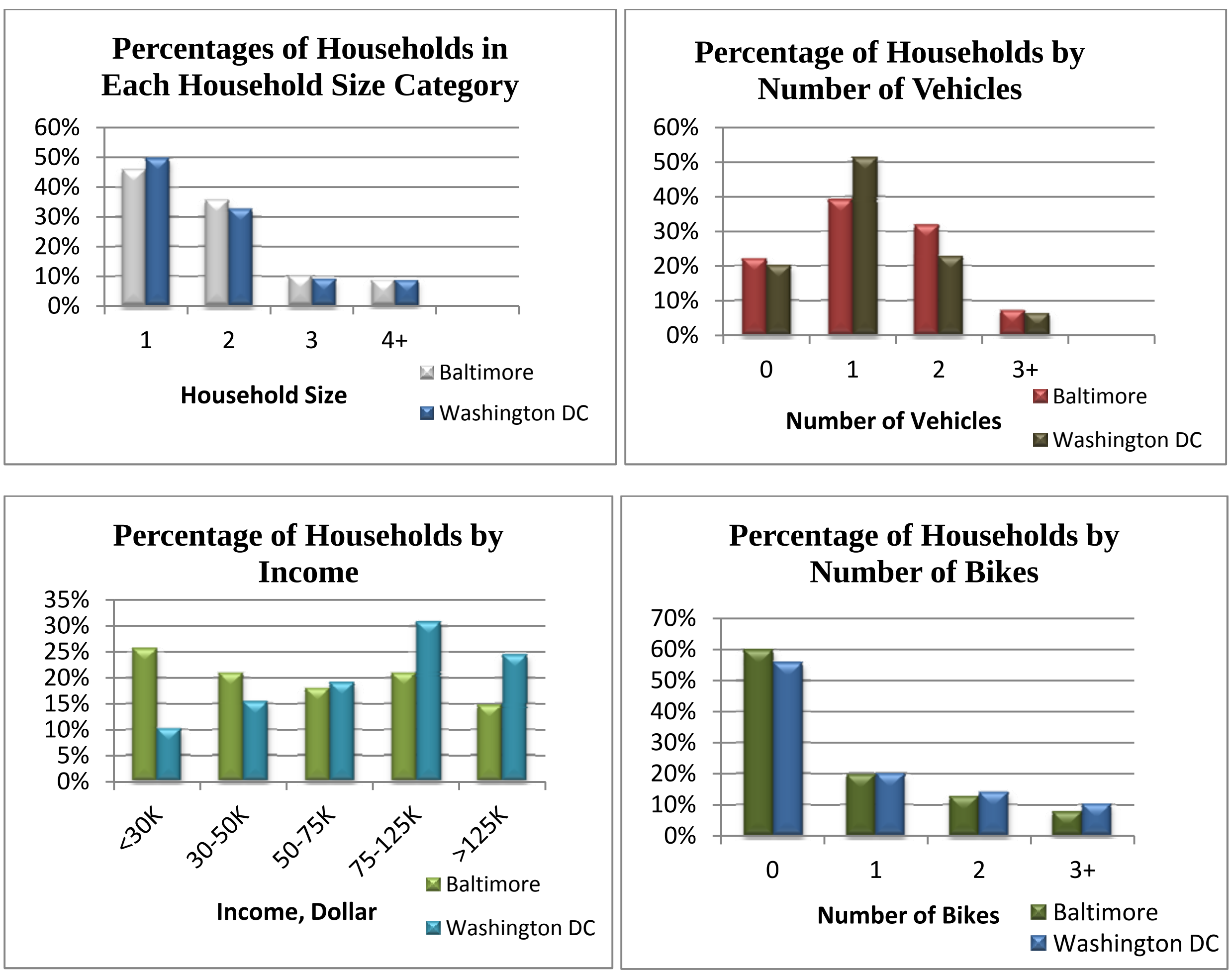



**Figure 19. A Comparison of Household Characteristics in Washington, D.C. and Baltimore TOD Areas.**

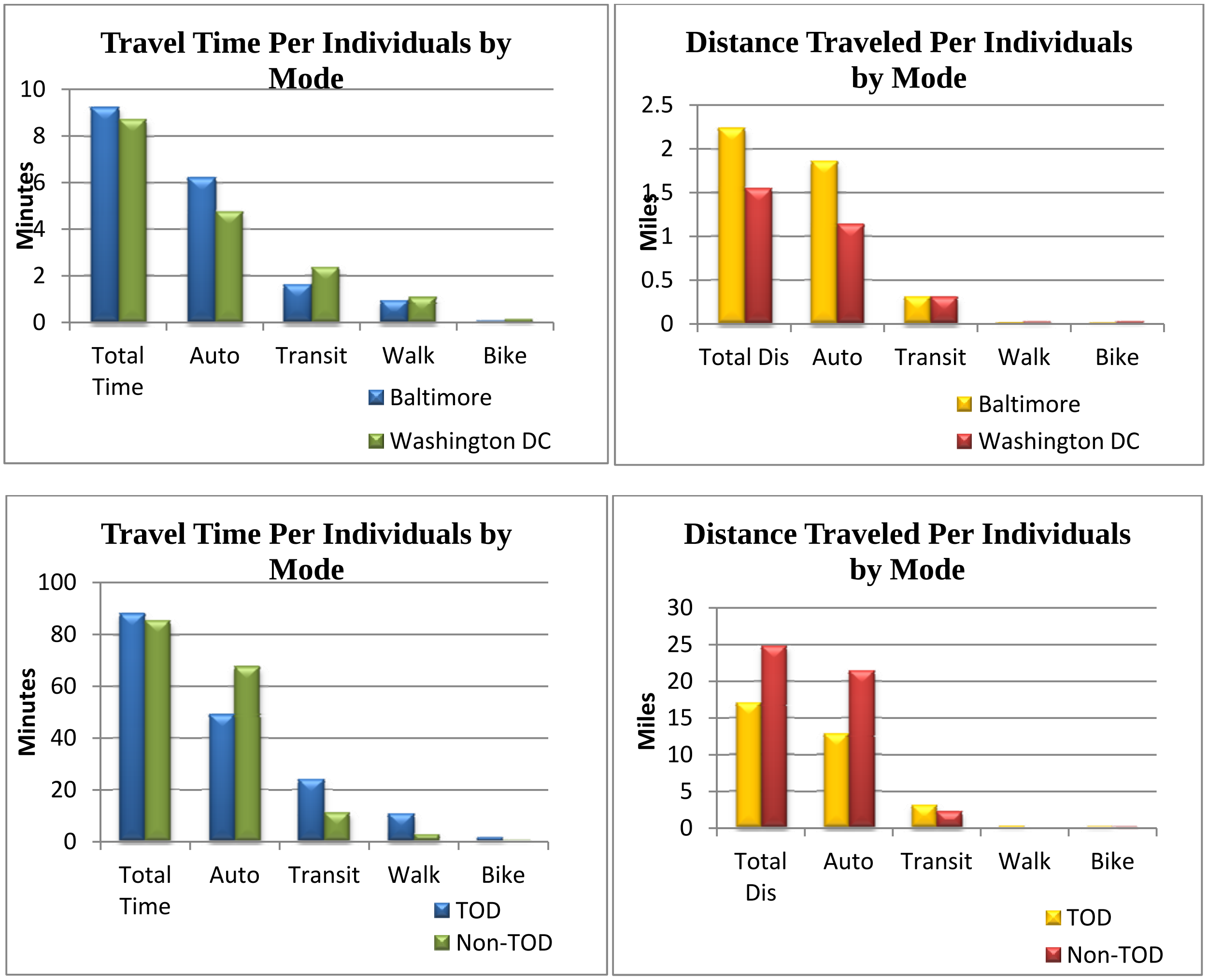



**Figure 20. A Comparison of Individuals Living in TOD and Non-TOD in the Washington, D.C., and Baltimore TOD Areas.**

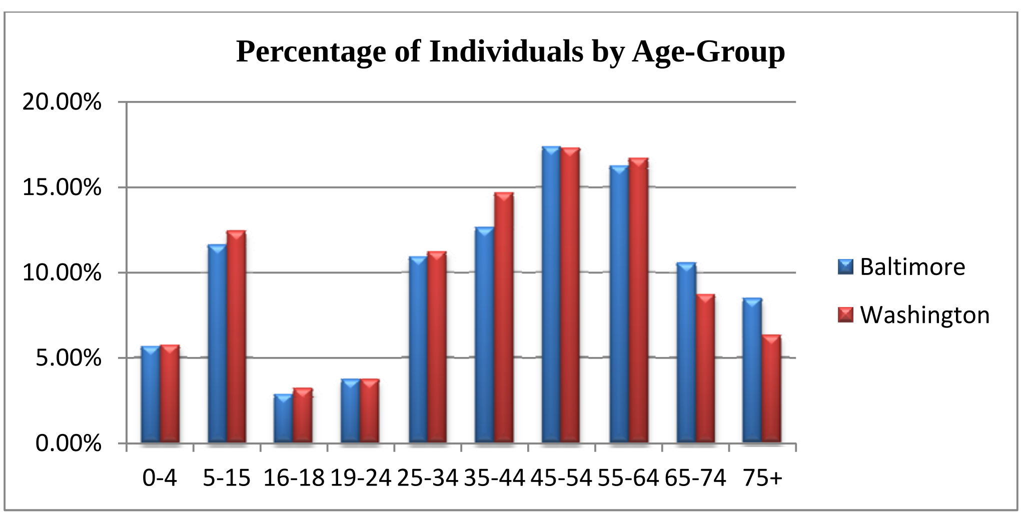



**Figure 21. Percentage of Individuals by Age Group in Baltimore and Washington, D.C.**

Table 4 summarizes the results and shows that people living in TOD areas have smaller households, most probably childless singles or couples or older, "empty-nester" couples who are unable or do not feel comfortable driving. TOD residents had lower car ownership rates than the non-TOD areas, as expected, and also lower annual income rates. The percentage of households with zero vehicles was 20 percent in TOD areas in Washington, D.C., and 23 percent in TOD areas in Baltimore, while it was only 5 percent and 9 percent in non-TOD areas. This huge difference and the average car ownership rates in TOD and non-TOD areas show that, in general, people living in TOD areas tend to drive less and have fewer automobiles. This is due either to lower needs or because parking space availability in the high-density urban areas is not as much as it is in low-density suburban areas.

**Table 4. Comparison of Selected Socioeconomic Characteristics in TOD & Non-TOD Areas.**

| | **Washington, D.C.** | | **Baltimore, MD** | |
|---|---|---|---|---|
| | TOD | Non-TOD | TOD | Non-TOD |
| **Average household size** | 1.81 | 2.29 | 1.74 | 2.20 |
| **Average auto ownership** | 1.12 | 1.86 | 1.19 | 1.68 |
| **Average annual income** | 7.60 | 7.73 | 5.72 | 7.11 |
| **Percentage of HHs with 0 vehicle** | 0.20 | 0.05 | 0.23 | 0.09 |

Table 5 summarizes the travel characteristics in TOD and non-TOD areas. In Washington, D.C., the percentage of transit/walk/bike trips is three times higher in TOD zones than in non-TOD zones. However, this difference is not as high in the Baltimore area. The table also separates work and non-work trips to understand how living in a TOD encourages transit use for shopping, recreational, and other non-work trips. It shows that in the Washington, D.C. area, the percentage of commute trips made by transit or non-motorized modes is almost half of all the work trips in TOD areas, and twice the percentage of transit work trips in non-TOD areas. The number of trips made by transit was much lower for non-work trips in both TOD and non-TOD areas in the Washington, D.C. metropolitan area. This might be because it is always easier to drive for shopping, recreational, and personal business trips, especially as people usually have company—husband and wife or parents with children—when making these kinds of trips. The results in Baltimore are somehow different than in the Washington, D.C. area. In Baltimore, people living in non-TOD areas commute by transit more than those in TOD areas (25 percent vs. 21 percent). However, the percentage of non-work trips in TOD areas made by transit was higher than the percentage of work trips. Similar to the pattern in Washington, D.C., the percentage of non-work trips made by transit, walk, and bike is lower in non-TOD areas than in the TOD areas where transit is more accessible and easier to use.

As it is shown in Table 5, TOD areas have lower rate of auto mode share in both Washington, D.C. and Baltimore metro areas regardless of trip purposes. The automobile mode share is higher in non-TOD areas as expected, though the difference is much greater in Washington than in Baltimore. The same pattern was observed when work and non-work trips were separated. In Washington, the difference in auto mode share between TOD and non-TOD areas was around 20 percent for both work and non-work trips, though the auto mode share was higher for non-work trips. In Baltimore, there was not that much of a difference observed among automobile mode share for work and non-work trips in TOD and non-TOD areas, but there was a slightly small difference between the auto share of non-work trips in TOD and non-TOD areas. This might be because in Baltimore there is not an extensive transit network as in the Washington area and the parking availability is much higher, which encourages people to drive more. It also reflects the fact that a great portion of workers living in Baltimore might actually have to commute to the Washington area for work.

**Table 5. Comparison of Selected Travel Characteristics in TOD and Non-TOD Areas.**

| | **Washington, D.C.** | | **Baltimore, MD** | |
|---|---|---|---|---|
| | TOD | Non-TOD | TOD | Non-TOD |
| **% all trips made by transit/walk/bike** | 35.65 | 13.49 | 22.22 | 17.87 |
| **% all trips made by auto*** | 61.79 | 82.57 | 73.56 | 78.73 |
| **% work trips made by transit/walk/bike** | 44.93 | 21.29 | 20.82 | 25.23 |
| **% non-work trips made by transit/walk/bike** | 32.79 | 11.18 | 23.78 | 15.62 |
| **% of work trips made by auto*** | 53.70 | 77.60 | 73.61 | 73.45 |
| **% of non-work trips made by auto*** | 64.63 | 84.15 | 73.54 | 80.41 |

* Auto trips considered both "driver" and "passenger" cases.

The descriptive statistics presented in table 5 help with making observations about the travel behavior pattern of people living in different areas with different land use characteristics and transit accessibility. However, it should be noted that these numbers alone do not necessarily prove that living in a TOD reduces automobile travel and increases transit use as several factors, such as self-selection and cultural identity, are involved in people's mode choice decisions for different trip purposes.

Figure 22 presents the number of trips made by households in TOD areas. The highest number of trips happened in TOD areas around Washington and the lowest happened in suburban areas away from Washington and Baltimore City.

Figure 23 presents activities that originated from a statewide TOD area. Washington TODs were the origins of most of the trips. Figures 24 and 25 show the distributions of the activity destinations that originated from a TOD area in Washington and Baltimore, respectively. The destinations in Washington were closer to the downtown, while the destinations in Baltimore were more wide spread.

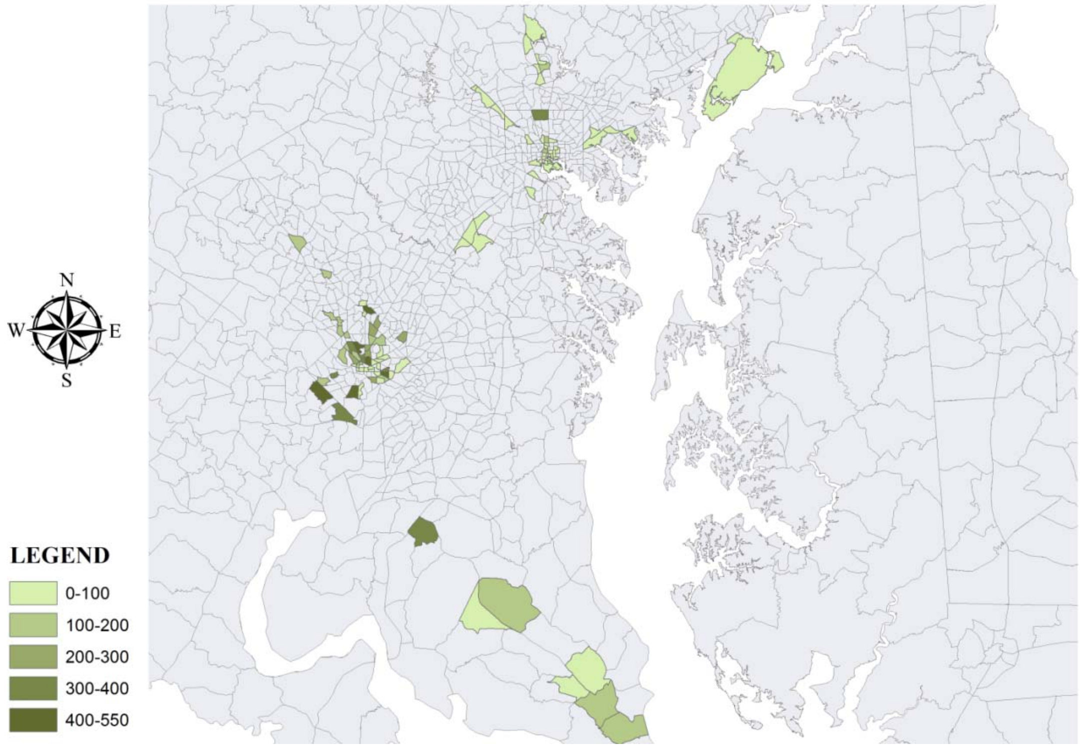



**Figure 22. Number of Trips Made by Households Living in Statewide TOD Areas.**

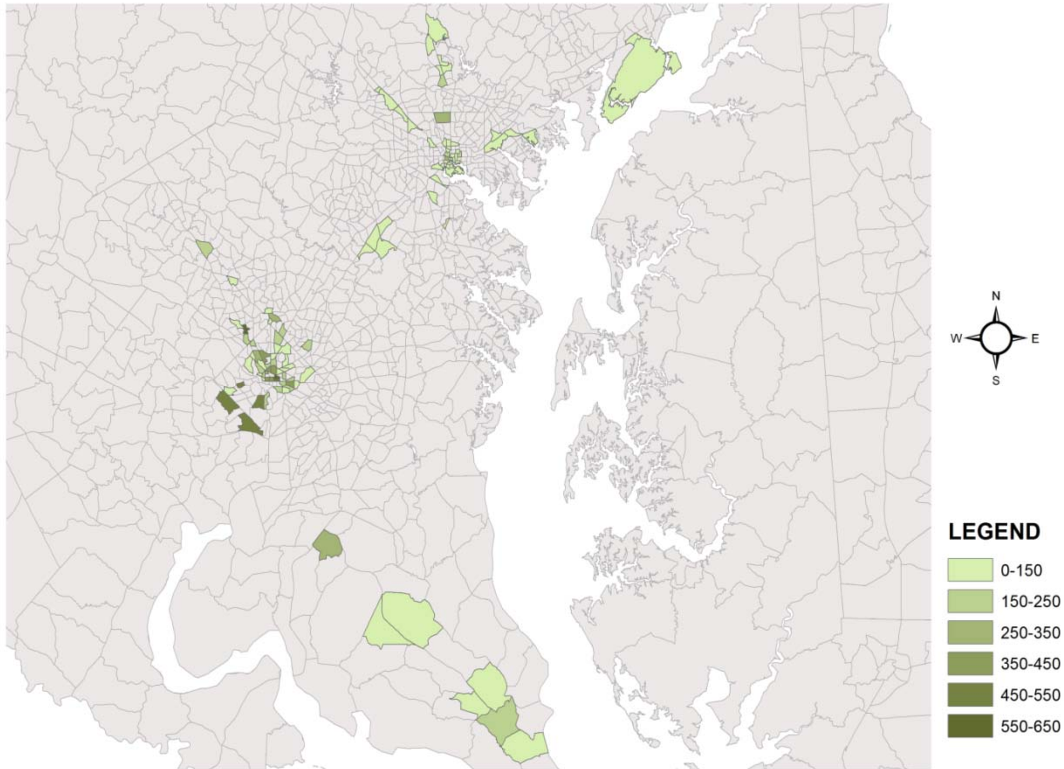



**Figure 23. Origin Distribution of Statewide TOD Areas.**

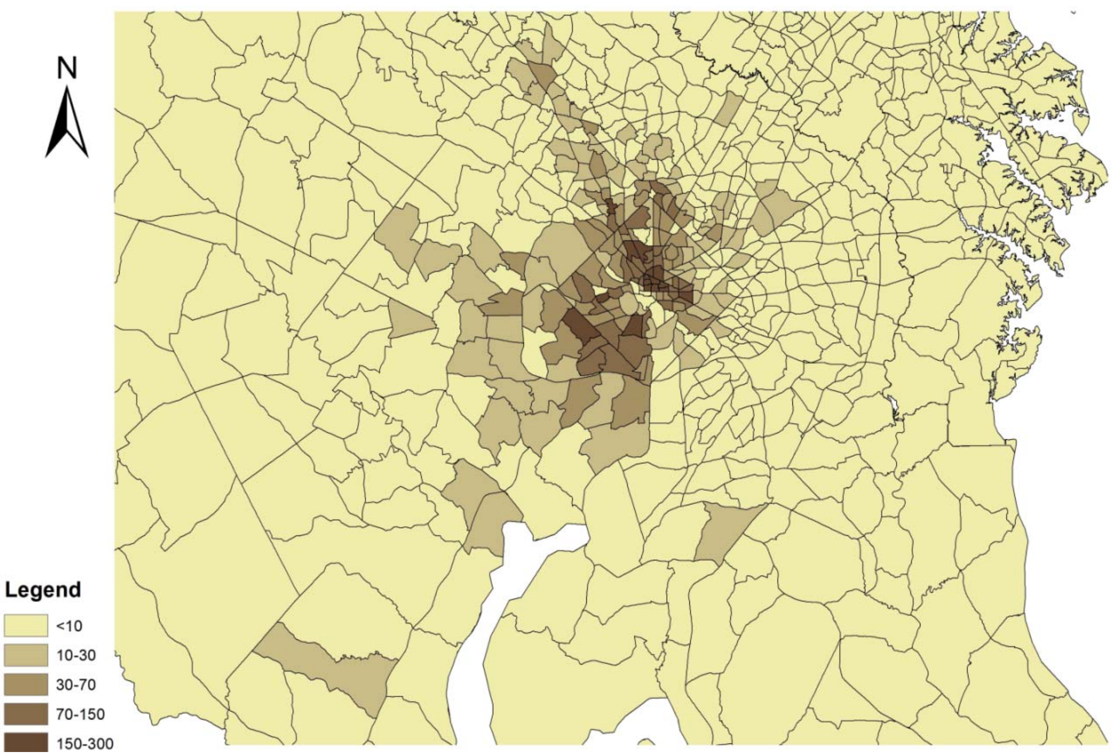



**Figure 24. Destination Distribution of Washington, D.C., TOD Areas.**

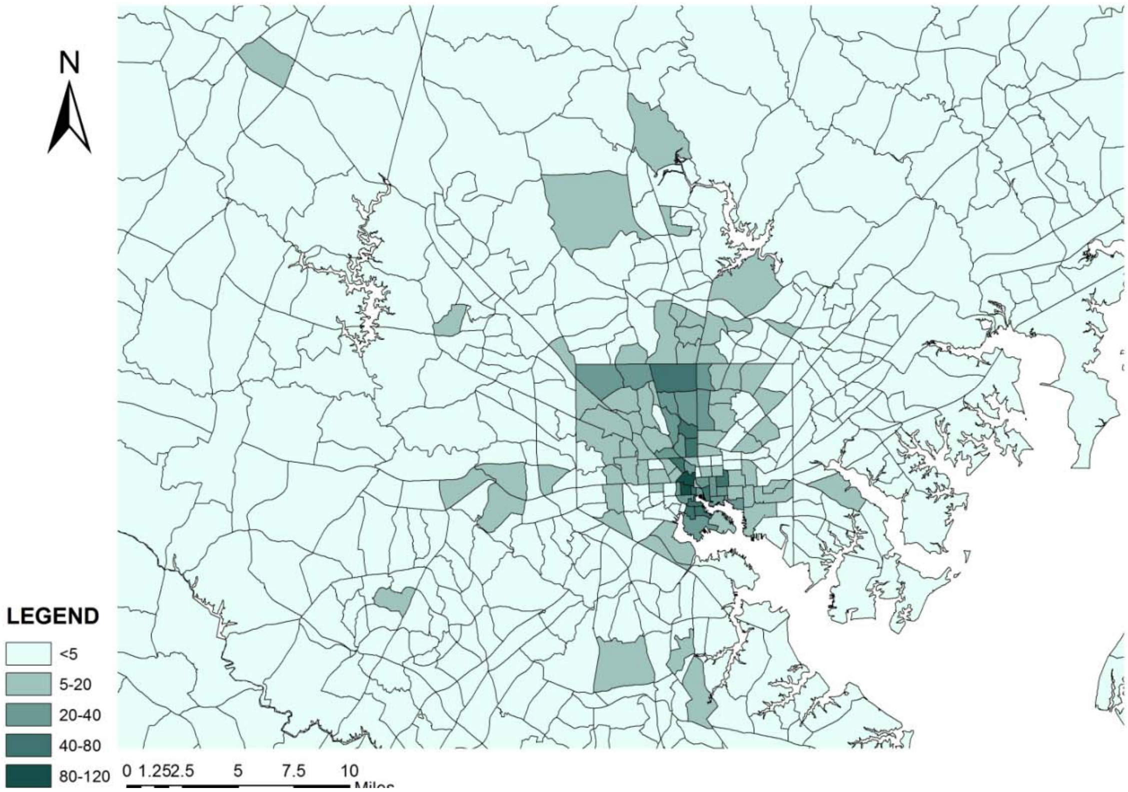



**Figure 25. Destination Distribution of Baltimore TOD Areas.**

Figure 26 illustrates activity origin distribution in TOD areas for transit mode. Washington SMZs were the origin of more activities and are therefore darker. Figure 27 shows activity origin distribution in TODs for automobile mode. Figure 27 indicates that the car is more popular in Baltimore than in Washington.

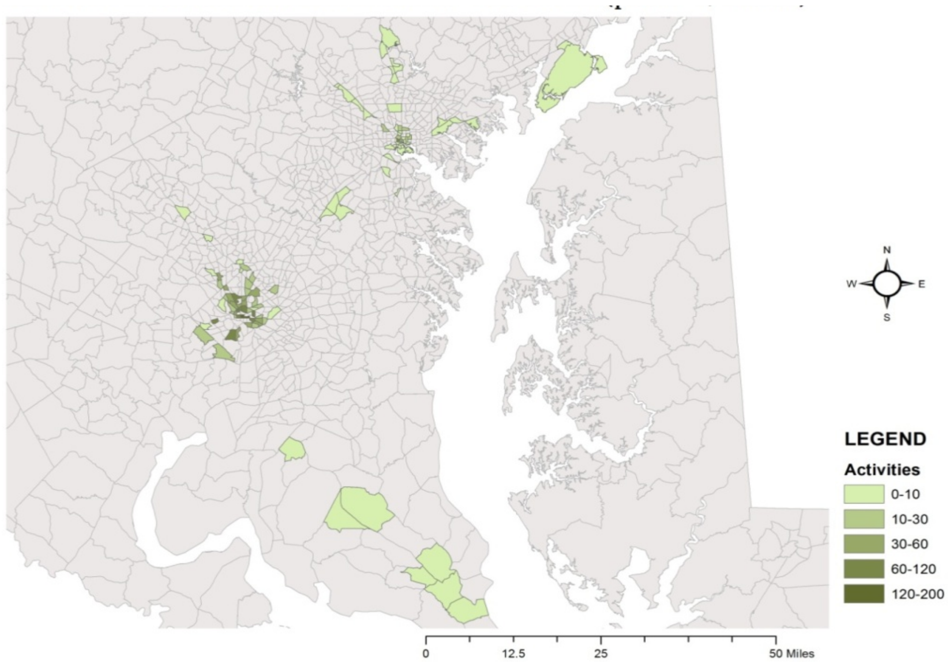



**Figure 26. Activity Origin Distribution in TOD Areas (Transit Mode).**

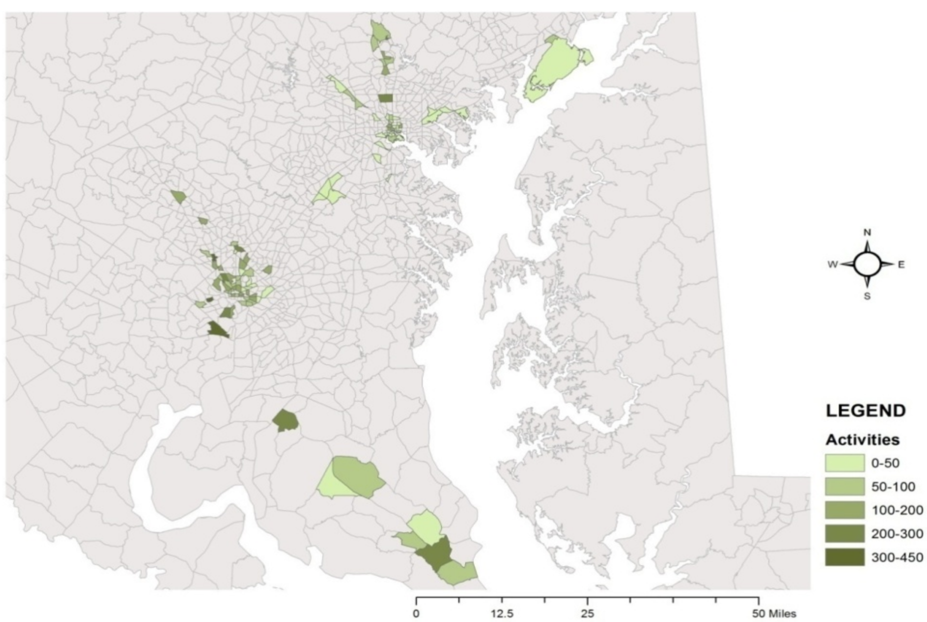
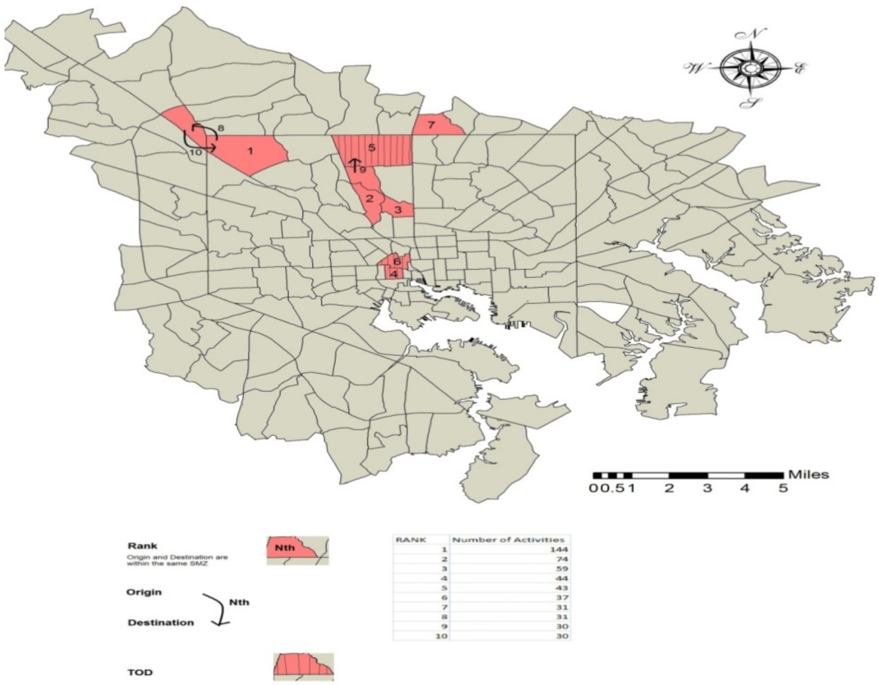



**Figure 27. Activity Origin Distribution in TOD Areas (Auto Mode).**

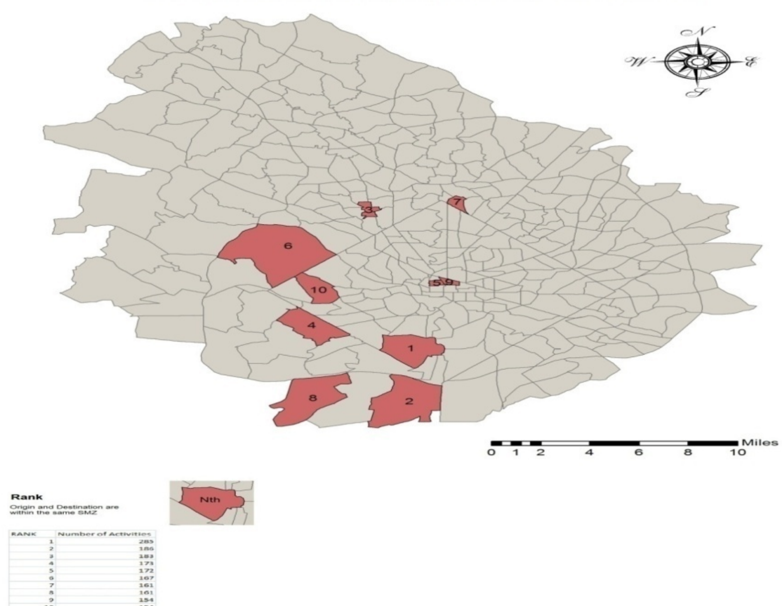
Figure 28 shows the top 10 inter-SMZ activities for Baltimore (highlighted SMZs are TOD). The rank (from 1 to 10) is written in each SMZ. Those without an arrow have the same origin and destination. Figure 29 shows the top 10 inter-SMZ activities for Washington, D.C., (highlighted

SMZs are TOD) and Figure 30 presents the top 10 inter-SMZ activities for both areas. All top 10 activities have the same origin and destination.




| RANK | Number of Activities |
|---|---|
| 1 | 144 |
| 2 | 74 |
| 3 | 59 |
| 4 | 44 |
| 5 | 43 |
| 6 | 37 |
| 7 | 31 |
| 8 | 31 |
| 9 | 30 |
| 10 | 30 |

**Figure 28. Top 10 Inter-SMZ Activities for Baltimore**




| RANK | Number of Activities |
|---|---|
| 1 | 285 |
| 2 | 186 |
| 3 | 183 |
| 4 | 173 |
| 5 | 172 |
| 6 | 167 |
| 7 | 161 |
| 8 | 161 |
| 9 | 154 |
| 10 | 154 |

**Figure 29. Top 10 Inter-SMZ Activities for Washington, D.C.**

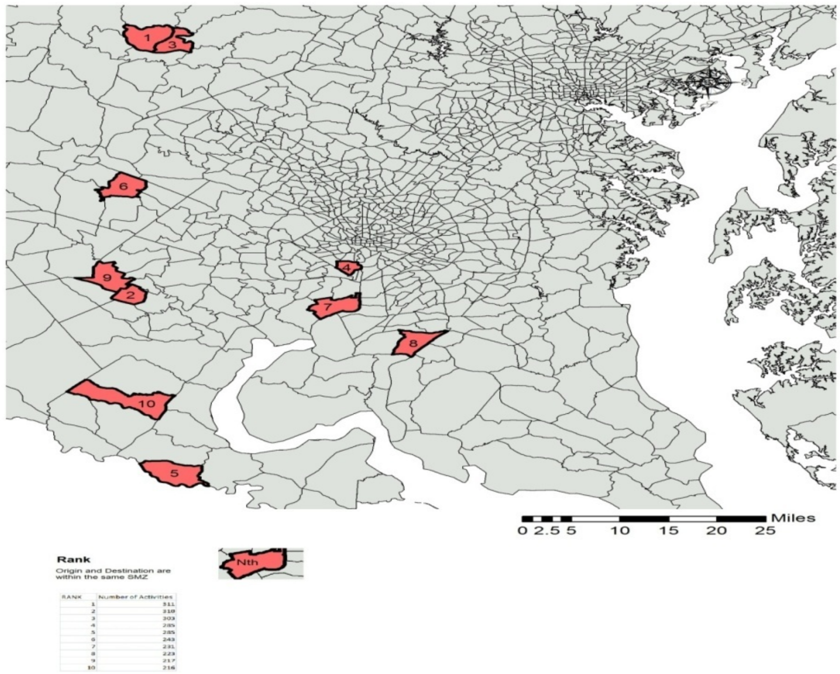



**Figure 30. Top 10 Inter-SMZ Activities for the Whole Area.**

### Statistical Analysis

The research team performed a t-test to compare the travel characteristics of households living in TOD versus non-TOD areas. The t-test finds whether the average values of TOD and non-TOD households are statistically different. Tables 6 and 7 present the results.

The t-test results are summarized below.

- Households living in a TOD area have **lower** total travel time (minutes) than those in a non-TOD area.
- Households living in a TOD area have **lower** auto travel time than those in a non-TOD area.
- Households living in a TOD area have **more** transit travel time than those in a non-TOD area.
- Households living in a TOD area have **more** walk travel time than those in a non-TOD area.
- Households living in a TOD area have **more** bike travel time than those in a non-TOD area.
- Households living in a TOD area have **less** distance traveled (miles) than those in a non-TOD area.
- Households living in a TOD area have **less** auto distance traveled than those in a non-TOD area.

- Households living in a TOD area have **more** transit distance traveled than those in a non-TOD area.
- Households living in a TOD area have **more** walking distance traveled than those in a non-TOD area.
- Households living in a TOD area have **more** biking distance traveled than those in a non-TOD area.

**Table 6. t-Test Results for Travel Time by Mode between TOD and Non-TOD Residents**

| Variables Tested | Mean | Variance | t-stat | df | P(T<t) one tail | P(T<t) two tail |
|---|---|---|---|---|---|---|
| **Total Travel Time in TODs** | 162.232 | 14173.530 | -10.461 | 2775 | 1.89E-25 | 3.77E-25 |
| **Total Travel Time in non-TODs** | 194.733 | 22897.820 | | | | |
| **Total Auto Travel Time in TODs** | 90.001 | 11014.624 | -23.097 | 2915 | 7.81E-109 | 1.56E-108 |
| **Total Auto Travel Time in non-TODs** | 154.077 | 20202.680 | | | | |
| **Total Transit Travel Time in TODs** | 43.778 | 5333.060 | 10.229 | 2289 | 2.38E-24 | 4.77E-24 |
| **Total Transit Travel Time in non-TODs** | 25.229 | 4406.376 | | | | |
| **Total Walk Travel Time in TODs** | 19.557 | 1248.280 | 16.333 | 1987 | 1.13E-56 | 2.27E-56 |
| **Total Walk Travel Time in non-TODs** | 5.732 | 379.390 | | | | |
| **Total Bike Travel Time in TODs** | 2.183 | 228.364 | 3.958 | 2002 | 3.91E-05 | 7.82E-05 |
| **Total Bike Travel Time in non-TODs** | 0.748 | 75.238 | | | | |

### Table 7. t-Test Results for Distance Traveled by Mode between TOD and Non-TOD Residents.

| Variables Tested | Mean | Variance | t-stat | df | P(T<t) one tail | P(T<t) two tail |
|---|---|---|---|---|---|---|
| **Total Distance Traveled in TODs** | 31.357 | 1487.774 | -24.478 | 3039 | 3.10E-121 | 6.30E-121 |
| **Total Distance Traveled in non-TODs** | 56.592 | 3012.773 | | | | |
| **Total Auto Distance Traveled in TODs** | 23.558 | 1287.081 | -26.029 | 3204 | 5.80E-136 | 1.20E-135 |
| **Total Auto Distance Traveled in non-TODs** | 48.870 | 2928.773 | | | | |
| **Total Transit Distance Traveled in TODs** | 5.636 | 177.631 | 2.196 | 2633 | 1.40E-02 | 2.80E-02 |
| **Total Transit Distance Traveled in non-TODs** | 4.883 | 247.197 | | | | |
| **Total Walk Distance Traveled in TODs** | 0.339 | 5.016 | 6.068 | 2020 | 7.68E-10 | 1.54E-09 |
| **Total Walk Distance Traveled in non-TODs** | 0.012 | 1.815 | | | | |
| **Total Bike Distance Traveled in TODs** | 0.261 | 3.615 | 3.546 | 2060 | 1.90E-04 | 3.99E-04 |
| **Total Bike Distance Traveled in non-TODs** | 0.097 | 1.563 | | | | |

## Multi-Level, Mixed Effect Modeling Results for VMT

After households with incomplete information were excluded, the dataset for the household-level VMT multi-level regression model contained 8,000 unique household observations in Washington, D.C., and more than 4,000 households in Baltimore.

The results from the multi-level, mixed effect model show a strong association among VMT, built environment characteristics, and living in a TOD. Tables 8 and 9 attempt to summarize the modeling results for the Washington, D.C., and Baltimore metropolitan areas, and are divided into three main sections: (1) the impact of households' socio-economic variables; (2) the impact of neighborhood-level, land-use factors; and (3) whether the household lives in a TOD area. The within and between-group variation (random effect) is also presented at the bottom of each table.

**Table 8. Results for the Multi-Level, Mixed-Effect Regression Model of Washington, D.C.**

| Dependent variable: Household's VMT-logged | Coefficient | Standard error | p-value |
|---|---|---|---|
| **Socioeconomic and control factors** | | | |
| **Constant** | 1.58 | 0.052 | 0.000 |
| **Household size** | 0.17 | 0.011 | 0.000 |
| **Household income** | 0.052 | 0.005 | 0.000 |
| **# of vehicles** | 0.28 | 0.014 | 0.000 |
| **# of workers** | 0.21 | 0.016 | 0.000 |
| **Built environment variables at local level** | | | |
| **Residential density** | -0.012 | 0.001 | 0.000 |
| **Employment density** | -0.002 | 0.0006 | 0.011 |
| **Land-use mix (entropy)** | -0.25 | 0.067 | 0.000 |
| **Distance from CBD** | 0.009 | 0.001 | 0.000 |
| **Average block size** | 0.44 | 0.086 | 0.000 |
| **Transit Accessibility- TOD Impact** | | | |
| **Household living in TOD** | -0.22 | 0.048 | 0.000 |
| **Covariance parameter estimates (random effect)** | | | |
| **TAZ** | 0.208 | 0.016 | |
| **Residual** | 0.977 | 0.007 | |

The research team controlled for the potential effects of socioeconomic status, using household size, annual income, number of workers in the household, and vehicle ownership in the model. The results showed that the socioeconomic variables significantly influenced the driving behavior and household VMT with a positive direction. This implies that the VMT increases with larger households that have higher annual income and car ownership. More workers in the household means different work locations, which forces household members to travel to different daily destinations. These numbers all make sense from the hypothetical point of view, as it is highly expected that households with these characteristics drive more and thus generate higher vehicle miles of travel.

**Table 9. Results for the Multi-level, Mixed Effect Regression Model of Baltimore.**

| Dependent variable: Household's VMT-logged | Coefficient | Standard error | p-value |
|---|---|---|---|
| **Socioeconomic and control factors** | | | |
| **Constant** | 1.77 | 0.083 | 0.000 |
| **Household size** | 0.093 | 0.015 | 0.000 |
| **Household income** | 0.085 | 0.007 | 0.000 |
| **# of vehicles** | 0.22 | 0.019 | 0.000 |
| **# of workers** | 0.29 | 0.023 | 0.000 |
| **Built environment variables at local level** | | | |
| **Residential density** | -0.015 | 0.0025 | 0.000 |
| **Employment density** | -0.0009 | 0.0008 | 0.258 |
| **Land-use mix (entropy)** | -0.21 | 0.088 | 0.019 |
| **Distance from CBD** | 0.010 | 0.003 | 0.000 |
| **Average block size** | 0.28 | 0.138 | 0.041 |
| **Transit Accessibility- TOD Impact** | | | |
| **Household living in TOD** | -0.24 | 0.087 | 0.005 |
| **Covariance parameter estimates (random effect)** | | | |
| **TAZ** | 0.21 | 0.027 | |
| **Residual** | 0.96 | 0.011 | |

As shown in tables 8 and 9, land-use variables at the neighborhood level, such as residential density, employment density, and the level of mixed use (entropy), have a negative relationship with VMT while the distance from the CBD and average block size (street connectivity) are positively linked to VMT. Overall, the coefficients of the land-use variables in the model, consistent with previous studies, show that people living in areas with a compact development pattern, higher employment opportunities, and better mixed neighborhoods tend to drive less as they can reach closer destinations by choosing non-motorized modes and transit. Distance to the CBD has a positive association with VMT, meaning people living farther from the CBD have to drive more to reach various destinations. The average block size as a measure of street network connectivity has a positive significant relationship with households' VMT. This is also because with smaller blocks in urban areas, which provide higher street connectivity, distance to various types of destinations is lower and, as a result, people drive less to reach those destinations. Also, lower block size aims to encourage more non-motorized trips as it is faster and more convenient for pedestrians and cyclists to reach destinations with smaller blocks.

More importantly, living in a TOD has a significant impact on the overall amount of driving of a household, even after controlling for other land-use factors. The results above clearly show that people who live within a half-mile distance of a major transit station with specific land-use characteristics tend to drive less and thus use transit or non-motorized modes of transportation more often. In comparison, the amount of driving and household VMT is significantly higher for those who live farther away from transit stations in low-density suburban areas where the only convenient—or sometimes the only accessible—mode of transportation is driving private automobiles.

From these results, one can also obtain the elasticity of VMT to TOD. It indicates that the VMT decreases by 19.6 percent in Washington, D.C., and 21.5 percent in Baltimore for people who live in a TOD area compared to non-TOD areas, all else being equal. These numbers prove the importance of pro-transit policies like TOD in reducing automobile travel. This will eventually aim to solve many transportation-related issues faced in urban areas and could be very instructive for policy and decision makers and planners.

These results clearly confirm the hypothesis proposed by TOD advocates who claim that TOD will change people's travel behavior towards a more sustainable way with less driving and more transit use, thus less traffic congestion and pollution. However, providing additional information—such as parking availability and price, and transit service quality in TOD areas—could be very helpful to assess a better and more reliable understanding of the potential impacts of TOD and/or other pro-transit policies on travel behavior and, more specifically, VMT. In the next sections, results from the trip generation and mode share analyses have been presented in order to show how mode-specific trip generation and the overall transit share is different in TOD and non-TOD areas.

**Trip Generation Modeling Results**

Descriptive statistics of trip generation rates for total and mode-specific trips are presented in figures 31 and 32 for Baltimore and Washington, D.C. The diagrams indicate that in the Baltimore metro area, in TOD zones, the average number of non-auto trips was higher, whereas in non-TOD areas the average number of auto trips was higher. These statistics show that, in general, TOD promotes non-auto mode choices, such as transit and walk/bike modes, but does not decrease the total number of trips.

In Washington, D.C., a similar pattern for trip generation was observed. The average number of auto trips produced by non-TOD residents was higher and the average number of non-auto trips was lower for these residents (see fig. 32).

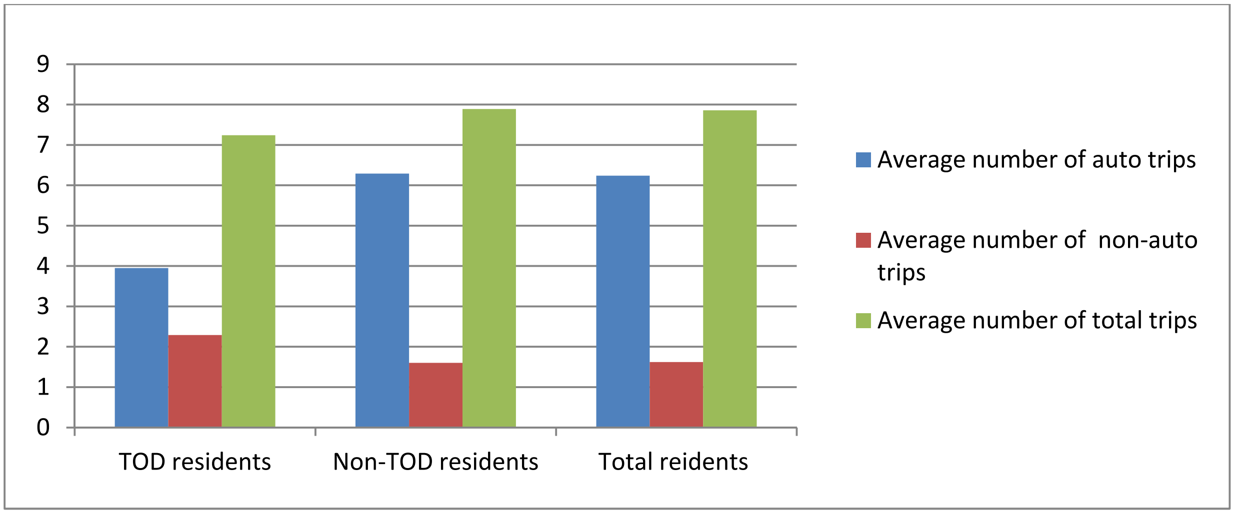



**Figure 31. Descriptive Statistics for Number of Trips in Baltimore.**

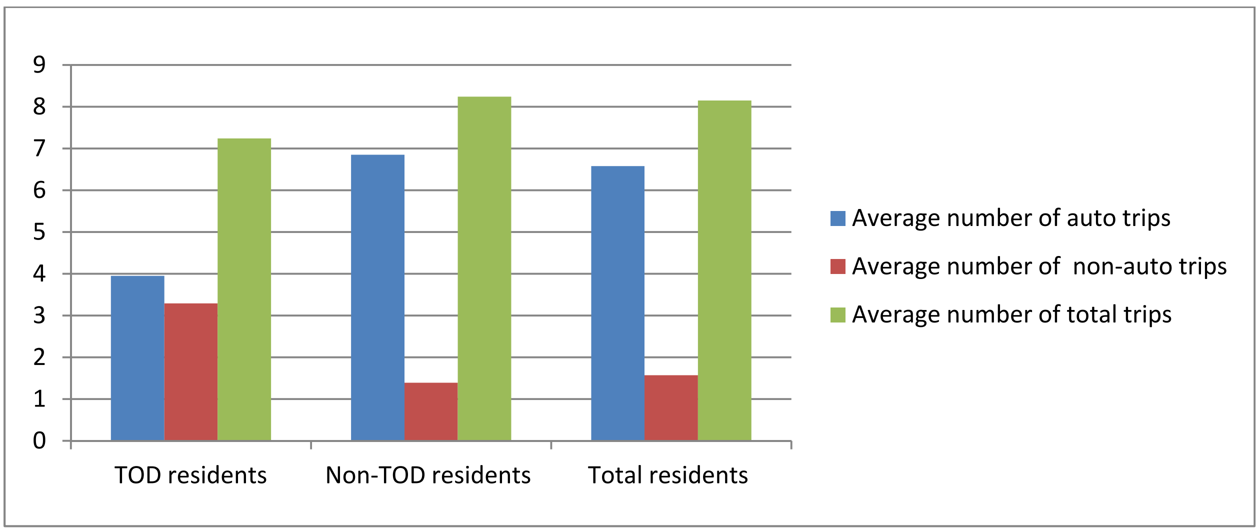



**Figure 32. Descriptive Statistics for Number of Trips in Washington, D.C.**

The statistical analysis shows that, overall, households living in TOD areas have fewer auto trips and more non-auto trips. To investigate the effect of TOD designation along with other factors, regression models were developed for the number of auto, non-auto, and total trips generated by households living in Washington, D.C., and Baltimore metropolitan areas.

Table 10 shows the regression modeling results developed for the total number of trips. It indicates that living in a TOD has a positive impact on the total number of trips made by each household. Households living in TOD areas in Washington, D.C., and Baltimore made about 0.5 and 0.3 more trips, respectively.

**Table 10. Trip Generation Model of Total Trips.**

| Dependent variable: Number of total trips per HH | | |
|---|---|---|
| **Independent Variables** | **Coefficient** | |
| **Area** | **Washington, D.C.** | **Baltimore** |
| **Household size** | 2.51 | 2.3 |
| **Household's # of workers** | -0.011* | 0.11 |
| **Household's # of children** | 0.88 | 0.97 |
| **Household's # of vehicles** | 0.23 | 0.32 |
| **Household's income** | 0.21 | 0.23 |
| **TOD** | 0.52 | 0.28* |
| **R-squared** | 0.81 | 0.81 |

* All the coefficients are significant at 95 percent confidence interval except these two coefficients.

Table 11 shows the results for the trip generation model developed for auto trips only. The dependent variable is the number of auto trips made by each household, and the independent variables include household size, number of workers, number of children, number of vehicles, household annual income, and a dummy variable for TOD (1 for TOD residents and 0 for non-TOD residents). The results show that if the household size increases by one unit in Washington, D.C., (i.e., one member is added to the household), the number of auto trips for that household will increase by 1.82. Households living in TOD areas have about 1.2 and 0.6 fewer auto trips than non-TOD residents in Washington, D.C., and Baltimore, respectively. This difference shows that TODs in these two metropolitan areas have different characteristics. For example, TODs in Washington, D.C., have more transit accessibility, a more efficient transit system, and less parking supply, which could potentially result in higher automobile trip reduction. Since the average number of auto trips was 6.6 and 6.2 in Washington, D. C., and Baltimore, respectively, there was an 18 percent reduction in auto trips in Washington, D. C., and 10 percent in Baltimore.

**Table 11. Trip Generation Model of Auto Trips.**

| Dependent variable: Number of auto trips per HH* | | |
|---|---|---|
| **Independent Variables** | **Coefficients** | |
| **Area** | **Washington, D.C.** | **Baltimore** |
| **HH size** | 1.82 | 1.44 |
| **HH number of workers** | -0.34 | -0.18 |
| **HH number of children** | 0.75 | 1.03 |
| **HH number of vehicles** | 1.06 | 1.38 |
| **HH income** | 0.1 | 0.08 |
| **TOD** | -1.22 | -0.59 |
| **R-squared** | 0.74 | 0.73 |

* All coefficients in this model are significant at 95percent confidence interval.

Table 12 shows the regression model results for non-auto trips. In this model, the dependent variable is the number of non-auto trips made by each household. The independent variables are similar to the previous model. Again, these results indicate that households living in a TOD area in Washington, D.C., make about 1.8 more trips than households living in a non-TOD area. For the Baltimore area, this effect is smaller (about 0.9 more trips).

**Table 12. Trip Generation Model of Non-Auto Trips.**

| **Dependent variable: Number of non-auto trips per HH** | | |
|---|---|---|
| **Independent Variables** | **Coefficient** | |
| **Area** | **Washington, D.C.** | **Baltimore** |
| **HH size** | 0.69 | 0.86 |
| **HH number of workers** | 0.33 | 0.29 |
| **HH number of children** | 0.13 | -0.06* |
| **HH number of vehicles** | -0.83 | -1.06 |
| **HH income** | 0.1 | 0.15 |
| **TOD** | 1.75 | 0.87 |
| **R-squared** | 0.42 | 0.39 |

* All the coefficients are significant at 95% confidence interval except this one.

In summary, the trip generation models show that living in a TOD could potentially reduce the number of auto trips. However, overall trip generation increases in TOD areas; as a result, trips made by non-automobile modes (i.e., walk/bike and transit) are higher in TOD areas than that in non-TOD zones.

**Mode Share Modeling**

In addition to VMT and trip generation, the research team also performed an analysis to see the effect of TOD on mode share. The key question the research team tried to answer is, how does transit-oriented development in a specific area affect the mode share of trips originating from that area?

First of all, descriptive statistics of mode share for the three primary modes are presented in figures 33, 34, and 35. The descriptive analysis results indicate that in both metropolitan areas, the percentage of auto mode share is higher in non-TOD zones, whereas the percentage of transit and non-motorized modes is higher in TOD zones. However, these effects were smaller in the Baltimore area as the TODs in Baltimore are not as extensive and efficient as in Washington, D.C., which has a unique and efficient rail transit system.


**Figure 33. Comparison of Auto Mode Share in Washington, D.C., and Baltimore.**

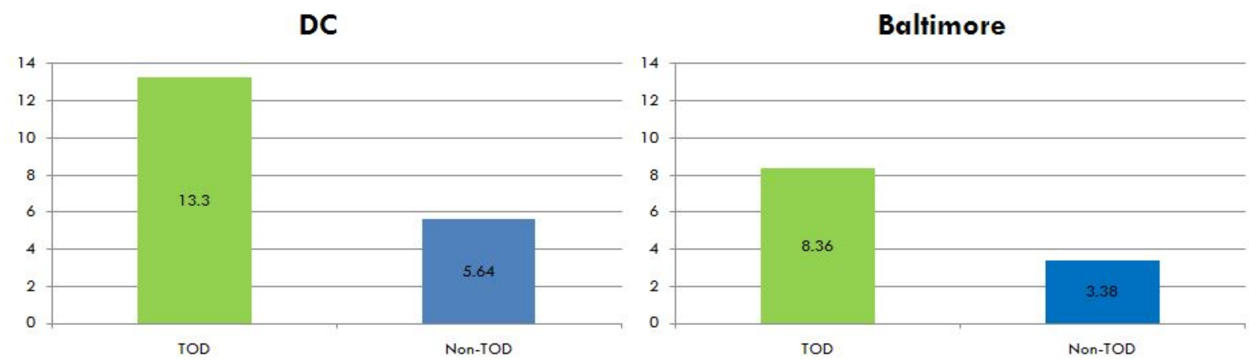



**Figure 34. Comparison of Transit Mode Share in Washington, D.C., and Baltimore.**

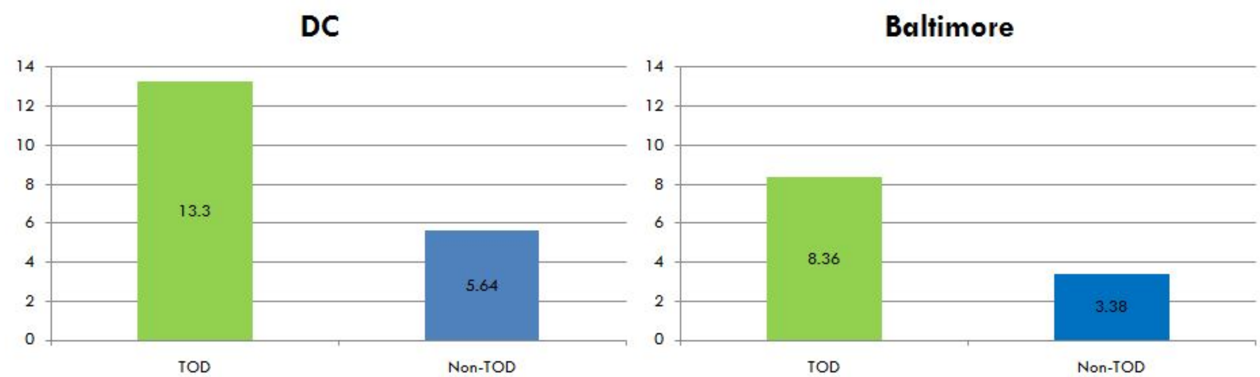



**Figure 35. Comparison of Walk/Bike Mode Share in Washington, D.C., and Baltimore.**

Next, the modeling results are discussed to investigate the effect of living in a TOD on mode share and to answer the aforementioned question. The research team modeled the mode share in

TOD and non-TOD areas using various land-use characteristics of the neighborhood of residence and socioeconomic and demographic variables of the households. The percent of the mode share of all trips originating from each TAZ is the dependent variable, and the independent variables include land-use variables (residential and employment densities and level of mixed-use development) and household characteristics (household size, income, and number of workers in the household). Since the model was at the zone level, all the household characteristics used were averaged from individual households to the entire households living in a specific zone. The research team included both land-use factors and household characteristics in the model to distinguish and evaluate the effect of each separately, and to prevent the overestimation of the effect of living in a TOD on mode choice. For example, if a household's share of transit trips is high because they do not have a car, the model would not take that as an advantage of TOD.

At the zone level, the mode share of auto, transit, and walk/bike are compared in TOD and non-TOD areas in Washington, D.C., and Baltimore. As expected, non-TOD residents had a 17 percent higher auto mode share in Washington, D.C., and a 14 percent higher auto mode share in Baltimore. Comparing these two cities, Baltimore appears to be a more auto-oriented city than Washington, D.C., due to the existence of a more efficient subway system in the capital city. Comparing transit mode share, the results confirmed the hypothesis that proximity to transit stations and living in a mixed and high-density area results in higher transit use. Also, Washington, D.C., had about a 5 percent higher transit mode share in both TOD and non-TOD areas. Descriptive statistics also indicated that among the three mode shares, walk/bike is most influenced by TOD designation. In both Washington, D.C., and Baltimore, living in a transit-oriented neighborhood results in about a 9 percent higher walk/bike mode share. These results only show the aggregate comparison between TOD and non-TOD and do not distinguish the effect of different land-use and household characteristics.

The research team performed the SUR modeling using three equations for the three primary modes, and the results indicated that trips originating from TOD in the Washington, D.C., metro area have significantly higher transit and walk/bike mode shares. In the first step, after controlling for socio-demographic factors, it was observed that living in a TOD results in a 12.13 percent decrease in auto transit and a 4.72 and 7.4 percent increase in transit and walk/bike mode share, respectively. Household size did not significantly affect the mode share of trips, while the number of workers in the household had a positive effect on transit mode share (see table 13). This could be explained as people usually use transit for commuting trips and as the number of workers increases, the transit mode share increases consequently. The modeling results also confirm the hypothesis that higher car ownership increases auto dependency and lowers transit ridership.

**Table 13. Mode Share Model in Washington D.C., First Step.**

| | Auto | Transit | Walk & Bike |
|---|---|---|---|
| **Dependent Variable: Mode Share Percentage** | | | |
| **HH Size** | -0.54 | -0.70* | 1.24* |
| **Income** | -0.29 | -0.48 | 0.77* |
| **Car Ownership** | 10.37* | -5.08* | -5.29* |
| **Avg # of Workers** | -3.30* | 2.52* | 0.78 |
| **Constant** | 72.11* | 17.32* | 10.57* |
| **HH Living in TOD** | -12.13* | 4.72* | 7.41* |

* Significant at 90% confidence interval

In the second step, after land-use variables were separated from TOD, the TOD coefficient showed that living in a TOD results in a 7.3 percent reduction in auto mode share and 3.75 and 3.55 percent increase in transit and walk/bike mode share, respectively. The coefficients for the land-use variables shows that, as expected, the urban area with higher densities and mixed-use development encourages more sustainable and environmentally friendly modes of transit and walk/bike and discourages automobile use. One unit increase in residential density would result in a 0.24 percent increase in walk/bike mode share and 0.12 percent increase in transit mode share (see table 14).

**Table 14. Mode Share Model in Washington, D.C., Second Step.**

| | Auto | Transit | Walk & Bike |
|---|---|---|---|
| **Dependent Variable: Mode Share Percentage** | | | |
| **Residential Density** | -0.36* | 0.12* | 0.24* |
| **Employment Density** | -0.10* | 0.02* | 0.08* |
| **Mixture-Entropy** | 1.78 | -2.10 | 0.34 |
| **HH Size** | -1.14* | -0.55 | 1.69* |
| **HH Income** | -0.08 | -0.54* | 0.62* |
| **Car Ownership** | 7.91* | -4.26* | -3.65* |
| **Average # of Workers** | -2.24 | 2.23* | 0.01 |
| **Constant** | 77.46* | 16.45* | 6.09* |
| **HH Living in TOD** | -7.30* | 3.75* | 3.55* |

* Significant at 90% confidence interval

In Baltimore, the results indicated that trips originating from a TOD have an 8.95 percent lower auto mode share and 2.46 and 6.49 percent higher transit and walk/bike mode share, respectively (see table 15 below). The average number of workers in a household living in each zone had a positive influence on transit mode share. If average car ownership increases by 1 unit (for example, the average number of autos per household changes from 1 to 2.), the auto mode share would increase by 7.52 percent and the transit and walk/bike mode share would decrease by 3.39 and 4.14 percent, respectively.

**Table 15. Mode Share Model in Baltimore, First Step.**

| | Auto | Transit | Walk & Bike |
|---|---|---|---|
| **Dependent Variable: Mode Share Percentage** | | | |
| **HH Size** | -1.16 | -0.41 | 0.75 |
| **Income** | -0.23 | -0.32* | 0.086 |
| **Car Ownership** | 7.61* | -3.43* | -4.18* |
| **Avg # of Workers** | -1.08 | 1.27* | 0.19 |
| **Constant** | 77.92* | 10.25* | 11.83* |
| **HH Living in TOD** | -8.95* | 2.46* | 6.49* |

* Significant at 90% confidence interval

In the second step, the results in Baltimore showed a somehow different trend than that in the Washington, D.C. area. The TOD coefficient indicated that its effect on mode share is not statistically significant in the Baltimore metro area. This may be due to weak performance of the transit systems in Baltimore and the fact that Baltimore does not have an efficient transit system as there is in the Washington, D.C. area. In Baltimore, in second step modeling, household size had a significant impact on mode share: the higher the number of people in a household, the greater the possibility that they used non-auto travel modes (see table 16).

**Table 16. Mode Share Model in Baltimore, Second Step.**

| | Auto | Transit | Walk & Bike |
|---|---|---|---|
| **Dependent Variable: Mode Share Percentage** | | | |
| **Residential Density** | -0.75* | 0.24* | 0.51* |
| **Employment Density** | -0.12* | 0.05* | 0.07* |
| **Mixture-Entropy** | -4.1* | -0.83 | 4.88* |
| **HH Size** | -1.80* | 0.52* | 1.28* |
| **Income** | -0.05 | -0.24* | 0.29* |
| **Car Ownership** | 3.08* | -1.91* | -1.17* |
| **Avg # of Workers** | 0.92 | 0.60 | -1.52* |
| **Constant** | 96.19* | 5.37* | 0.58* |
| **HH Living in TOD** | -0.86 | 0.28 | 0.58 |

* Significant at 90% confidence interval

The effect of socioeconomic and demographic variables was the same in both metro areas in terms of direction but not magnitude. A household's income had a significant positive effect on walk/bike mode share, which was consistent with the results of previous empirical studies. After controlling for auto ownership, income did not have a significant effect on auto mode share for either of the models of Baltimore and Washington, D.C. As expected, car ownership was the most influential factor in determining the mode of travel in both Washington, D.C., and Baltimore.

Looking at the land-use coefficients, the results are inconsistent and, to some extent, not as expected for the effect of entropy. In Washington, D.C., the level of mixed use (entropy) had a positive but statistically insignificant influence on auto mode share. In contrast, in the Baltimore area, entropy had a significant and negative influence on auto mode share. To check whether the model generated reasonable results, the research team assumed a TAZ with 100 people per acre residential density and employment density as the extreme case. The research team put these numbers into the model for the Washington, D.C., case and used the average for other variables. The results showed 35 percent auto mode share, 28 percent transit mode share, and 37 percent walk/bike mode share. These results confirmed that even in extreme cases, the model would not generate unrealistic outputs.

Based on the modeling results, residential and employment density both have a significant effect in increasing non-auto mode share. Furthermore, when only controlled for households' characteristics, modeling results showed that trips originating from a TOD have about ten percent less auto mode share.

### The Effect of TOD on Transportation Models

As stated earlier, the research team performed cross-classification and regression models for trip productions. Table 17 presents the new trip rates obtained from the cross-classification method.

**Table 17. Trip Production Rates by Area Type and Trip Purpose.**

| | HBW | | | | HBS | | | | HBO | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wrks0 | Wrks1 | Wrks2 | Wrks3+ | Size 1 | Size 2 | Size 3 | Size 4+ | Size 1 | Size 2 | Size 3 | Size 4+ |
| **TOD/AREA 1** | 1.9487 | 1.7392 | 2.6583 | 4.0327 | 1.5237 | 2.3882 | 2.7314 | 3.6475 | 1.8710 | 2.8595 | 3.3838 | 4.8361 |
| **TOD/AREA 2** | 2.0250 | 1.7142 | 2.7685 | 4.2514 | 1.6042 | 2.3085 | 2.8739 | 3.7359 | 1.8844 | 2.8720 | 3.7281 | 5.2057 |
| **TOD/AREA 3** | 1.7600 | 1.6929 | 2.7551 | 3.9268 | 1.5719 | 2.3527 | 2.6806 | 3.5367 | 1.9036 | 2.7766 | 3.6035 | 5.2821 |
| **TOD/AREA 4** | 1.4000 | 1.6774 | 2.5739 | 4.3889 | 1.4524 | 2.1765 | 2.4390 | 3.9667 | 2.0196 | 2.8154 | 3.4318 | 5.2955 |
| **TOD/AREA 5** | 1.5556 | 1.6835 | 2.7799 | 4.1739 | 1.6667 | 2.4500 | 3.2540 | 3.3778 | 1.9724 | 2.6290 | 3.5909 | 4.8955 |

| | NHBW | | | | NHBO | | | | HBSCH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wrks0 | Wrks1 | Wrks2 | Wrks3+ | Size 1 | Size 2 | Size 3 | Size 4+ | Size 1 | Size 2 | Size 3 | Size 4+ |
| **TOD/AREA 1** | 1.7826 | 1.7885 | 2.2237 | 2.8043 | 2.1825 | 3.0681 | 3.2432 | 4.1375 | 1.0000 | 1.9310 | 1.9236 | 3.4380 |
| **TOD/AREA 2** | 1.4762 | 1.7337 | 2.2546 | 2.4483 | 2.0972 | 2.8098 | 3.0494 | 3.8672 | 1.5714 | 1.9057 | 2.1070 | 3.4691 |
| **TOD/AREA 3** | 1.3333 | 1.7967 | 2.6192 | 2.2586 | 1.9695 | 2.6885 | 2.9330 | 3.9066 | 1.6190 | 1.8901 | 2.0410 | 3.2536 |
| **TOD/AREA 4** | 1.0000 | 1.7759 | 2.4884 | 2.5000 | 2.0556 | 2.5610 | 3.4651 | 3.2000 | 2.0000 | 1.7143 | 1.9615 | 3.9756 |
| **TOD/AREA 5** | 1.7500 | 1.9827 | 2.8068 | 2.5714 | 2.0256 | 2.4273 | 3.2000 | 4.0000 | 1.5909 | 1.8409 | 1.9286 | 3.1000 |

The calculated trip rates were different from the original rates; however, they could not be applied to the MSTM model since the codes accept only three regions. The MSTM codes were not available to the research team to change; therefore, the research team decided to make a regression model for trip productions.

The total number of motorized trips done by each household was categorized (classified by trip purposes) as a dependent variable. To be consistent with the MSTM model, income, household size, and the number of workers in the household were considered the independent variables. Six different datasets were created, one for each trip purpose. The correlation between every two variables was calculated for each dataset. Finally, forward and backward regression was applied to the 14,363 households for each trip purpose to find the regression models with the highest goodness of fit. Table 18 presents the regression results.

For work trips (HBW and NHBW), the independent variables were the number of workers, income groups, and TOD; for non-work trips, they were HH size, income groups, and TOD (HBSch) or TOD/area type.

The HTS data included nine income groups; however, the research team combined the groups and made five income groups to be consistent with the MSTM. The income groups are as follows*:*
Group 1: Low income (less than $30,000)
Group 2: Medium-Low income ($30,000-$60,000)
Group 3: Medium income ($60,000-$90,000)
Group 4: Medium-High income ($90,000-$150,000)
Group 5: High income ($150,000 and more)

Four dummy variables (Income1-Income4) were defined by the research team to represent the income groups.

The research team calculated trip production rates for each SMZ using the regression equations. The average values of the independent variables were calculated for each SMZ. However, since the 14,363 households live in only 919 SMZs, the new trip rates were calculated only for the 919 SMZs and the rest of SMZs' trip rates remained unchanged. Trip ends or number of trips were calculated by multiplying the trip rates by the number of households in each SMZ. Out of 683 SMZs for which the data was not available (figure 36), 12 were TOD, 651 were non-TOD, and the rest were out of the BMC/MWCOG area. Also, out of the 683 SMZs, 505 were rural, 124 were suburban, 40 were urban, and 14 were out of BMC/MWCOG area.

After changing trip productions for the 919 SMZs, the research team balanced attractions to productions for HBW, HBS, and HBO trips, and productions to attractions for HBSch, NHBW, and NHBO trips. The balanced trip productions and attractions were fed to the MSTM to run. Table 19 presents vehicle miles traveled in the original MSTM model versus the proposed model. In major counties in the state of Maryland, the VMT reduced considerably for counties that can be considered TOD such as Baltimore City, Baltimore County, Montgomery County, and Prince George's County. The VMT did not significantly change for non-TOD counties such as Howard County. The research team also compared the link volumes for the two models. On average, the link volumes reduced 2 percent in the suggested model compared to the original MSTM. However, the average link volumes only for TOD areas were 17 percent less than the original MSTM. Therefore, there were fewer trips in TOD areas compared to non-TOD areas. The suggested model is not calibrated since the research team is unable to access the MSTM source codes; therefore, a fair comparison is not possible. However, the aforementioned comparisons show that by taking TOD into account, the model results are significantly different for TOD areas; therefore, the whole transportation network will have different characteristics such as congested volume and travel time. Consequently, the research team suggests MSTM developers include TOD in the model.

**Table 18. Regression Results for 14,363 Households by Each Trip Purpose.**

| | Model/Trip Purpose | | | | | |
|---|---|---|---|---|---|---|
| | **HBW** | **HBS** | **HBSch** | **HBO** | **NHBW** | **NHBO** |
| **Independent Variables** | Coeff. (p-value) | Coeff. (p-value) | Coeff. (p-value) | Coeff. (p-value) | Coeff. (p-value) | Coeff. (p-value) |
| **# of Workers** | 1.1181 (0.00E+00) | ----- | ----- | ----- | 0.4964 (0.00E+00) | ----- |
| **HH Size** | ----- | 0.4078 (0.00E+00) | 0.4123 (0.00E+00) | 0.7052 (0.00E+00) | ----- | 0.4349 (1.35E-288) |
| **Income group 1** | 0.1100 (2.47E-05) | 0.1788 (1.29E-04) | -0.4060 (8.73E-61) | 0.0871 (1.44E-01) | -0.0318 (2.10E-01) | 0.3345 (7.10E-09) |
| **Income group 2** | 0.1146 (2.16E-08) | 0.2508 (4.08E-11) | -0.4660 (5.47E-125) | 0.1980 (4.38E-05) | 0.0438 (2.78E-02) | 0.4604 (1.24E-22) |
| **Income group 3** | 0.0974 (3.99E-06) | 0.3300 (2.00E-18) | -0.4938 (1.10E-134) | 0.2640 (3.90E-08) | 0.1045 (3.71E-07) | 0.4995 (8.99E-27) |
| **Income group 4** | 0.0479 (3.86E-02) | 0.3633 (5.35E-20) | -0.4899 (1.18E-113) | 0.1896 (1.77E-04) | 0.1184 (1.56E-07) | 0.4131 (3.67E-17) |
| **TOD** | -0.1178 (9.87E-06) | ----- | -0.0875 (2.11E-04) | ----- | -0.0497 (5.56E-02) | ----- |
| **TOD/AREA** | ----- | -0.0417 (1.49E-05) | ----- | -0.0441 (3.33E-04) | ----- | -0.0823 (5.15E-12) |
| **Adj R2** | 0.7035 | 0.3340 | 0.3618 | 0.4280 | 0.3517 | 0.2788 |

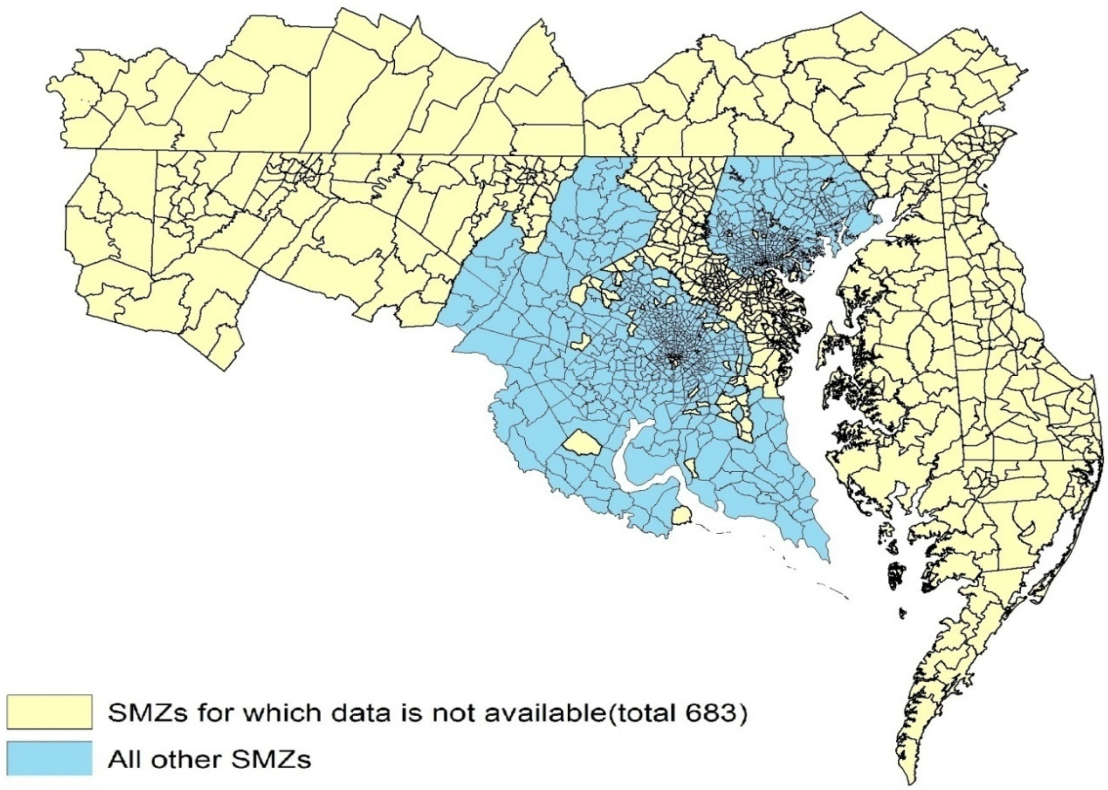



**Figure 36. Available Data vs. Unavailable Data.**

## Table 19. Comparisons of the VMT and VHT of the Proposed Model and the Original MSTM.

| | Original MSTM | | *Proposed Model* | |
|---|---|---|---|---|
| **County** | **VMT** | **VHT** | **VMT** | **VHT** |
| **ALLEGANY** | 2112505.08 | 194813682 | 2112845.91 | 194827538 |
| **ANNE_ARUNDEL** | 15535046.7 | 1873554192 | 14954929.4 | 1774653123 |
| **BALTIMORE_CO.** | 23286941.4 | 2710009797 | 18924526.1 | 2066905537 |
| **CALVERT** | 1503337.8 | 230643379 | 1104045.91 | 141226651 |
| **CAROLINE** | 1201937.32 | 132062720 | 1204113.45 | 132315566 |
| **CARROLL** | 5037486.19 | 648712779 | 4858561.22 | 622804474 |
| **CECIL** | 5009337.16 | 497093635 | 5003435.09 | 495870985 |
| **CHARLES** | 2790588.5 | 335152511 | 2053124.92 | 239366330 |
| **DORCHESTER** | 1082533.13 | 119630754 | 1083634.04 | 119744209 |
| **FREDERICK** | 8108394.89 | 868685582 | 6484849.61 | 622245284 |
| **GARRETT** | 1555369.74 | 143964712 | 1555782.14 | 143987494 |
| **HARFORD** | 7638393.58 | 842917459 | 6145948.5 | 635045036 |
| **HOWARD** | 10801445.4 | 1157106636 | 10056121.7 | 1067884549 |
| **KENT** | 627173.65 | 67494554.4 | 622526.96 | 67042910.5 |
| **MONTGOMERY** | 18315390.7 | 2549252544 | 14035896.7 | 1808186456 |
| **PRINCE_GEORGES** | 19077772.7 | 2530779260 | 14485825.9 | 1731132331 |
| **QUEEN_ANNES** | 2098574.69 | 228152998 | 2076829.44 | 225976576 |
| **ST._MARYS** | 2810118.95 | 342778443 | 2072325.84 | 237751186 |
| **SOMERSET** | 835524.16 | 88534350.7 | 835471.08 | 88509746.9 |
| **TALBOT** | 1416920.45 | 189212089 | 1434201.77 | 191327241 |
| **WASHINGTON** | 5011091.4 | 476739065 | 4958712.09 | 470926885 |
| **WICOMICO** | 2616305.53 | 423775991 | 2628392.67 | 422736035 |
| **WORCESTER** | 1499033.54 | 168972160 | 1497767.53 | 168804818 |
| **BALTIMORE_CITY** | 9368592.53 | 1363203783 | 7589933.46 | 1066303807 |
| **Sum** | 149339815.2 | 18183243076 | 127779801.4 | 14735574768 |

## ECONOMIC EVALUATION

In addition to the impacts of TOD on changing travel behavior—which was analyzed and explained in the previous sections—TOD is also recognized as a solution to cope with traffic congestion, air pollution, and environmental emissions through encouraging transit use and other sustainable modes as opposed to driving. However, the actual effect of TOD on congestion reduction and on the environment have not been extensively tested and evaluated. The research team developed prototype tools to analyze the impact of behavioral changes induced by TOD on congestion, pollutions, and greenhouse gas (GHG) emissions. TOD scenarios in the Washington, D.C. metropolitan area and specifically along the Intercounty Connector (ICC)[3] were evaluated, and the effect of TOD on traffic congestion was quantitatively modeled using a large-scale microscopic traffic simulation approach (i.e., over 7,000 links, 3,500 nodes, and over 540,000 vehicles simulated) developed specifically for the study area. Traffic conditions on both the corridor level and whole-network level were analyzed and modeled for TOD and non-TOD zones.

For the emission analysis, the research team used the well-known MOVES (Motor Vehicles Emission Simulator) model developed by the Environmental Protection Agency (EPA) as a post-processing module and estimated the total emission and fuel consumption throughout the whole study area to investigate the potential environmental benefits of TOD.

The complete steps of the study and modeling approaches are presented in figure 37. As mentioned in the previous sections, this research started with identifying TOD zones within the study area using a unique quantitative method and developing a trip generation regression model to specify the overall demand using recent travel survey data. The trip generation model and TOD identification procedure are denoted as the TOD module. The result of the TOD module was then used as the input for simulation modeling. After the simulation procedure was done, the performance of the network before and after the TOD scenario, as well as the emissions estimation model, were linked to conduct the environmental impact analysis.

[3] Maryland Route 200

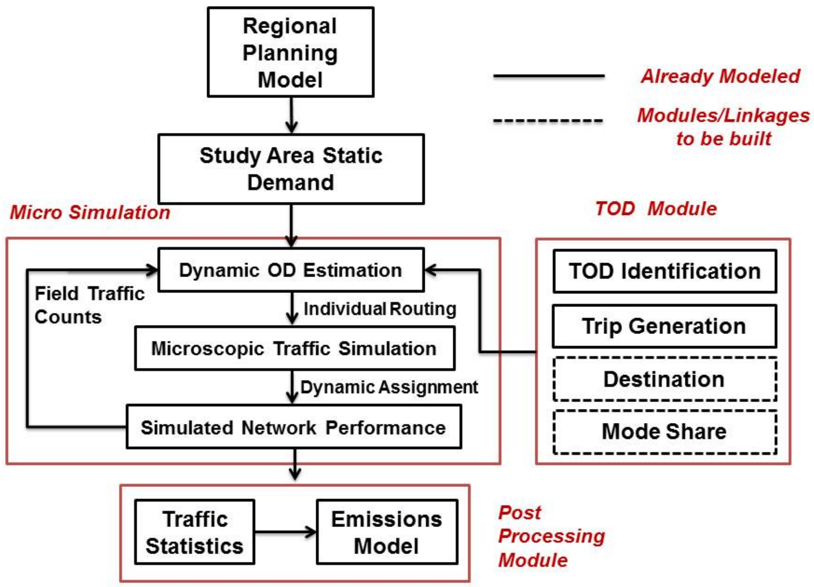



**Figure 37. Flow Chart of Steps in the Analysis.**

The result of the auto trip generation regression model for Washington, D.C. presented in table 7 indicated that households living in a TOD make 1.22 trips less than those living in non-TOD zones. Dividing this number by the average number of auto trips resulted in approximately 20 percent less trips for TOD residents. This percentage reduction in auto trips was used to build the simulation model by applying the percentage reduction in auto trips in TOD zones to the zone-based, origin-destination trip table. This modified trip table was then used in the simulation process to analyze the effect of TOD on road network traffic flow and congestion.

### Large-scale Microscopic Traffic Simulation Model

A microscopic traffic simulation model was developed for this analysis which was built in TransModeler software package. The study area of this simulation model includes all freeways (highlighted as thick blue solid lines in figure 38), major arterials (highlighted as yellow solid lines), minor arterials (highlighted as green solid lines), and some local streets (other lines in figure 38) along the I-270/I-495/I-95 corridor in the north Washington D.C. metropolitan area. It covers central and eastern Montgomery County and northwestern Prince George's County, where several new developments, such as the Great Seneca Science Corridor (GSSC) in west Gaithersburg and military bases in Fort Meade, have been proposed. MD 200, the Intercounty Connector, a new toll road built in 2011, also traverses this area.

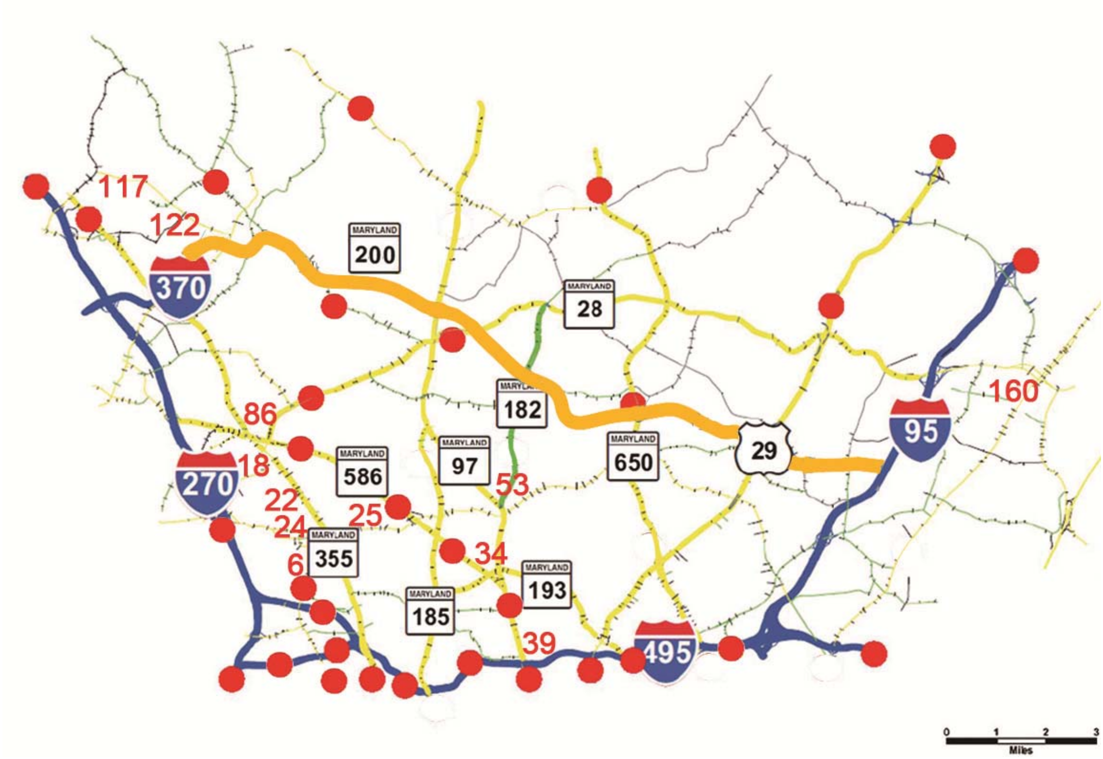



**Figure 38. Simulated Network in the Study Area and the Location of TODs.**

The simulated network was developed based on satellite images of this area provided by Google Earth and the end product conformed to the true geometry with very high accuracy. On the network supply side, a total number of 7,121 links and 3,521 nodes were constructed.

Various input data were needed for developing a microscopic traffic simulation study on such a large scale, including multimodal origin-destination (OD) travel demand information, intersection signal timing data, ground truth traffic information for calibration/validation, and so forth. The baseline multimodal OD travel demand information was obtained from the Metropolitan Washington Council of Government (MWCOG) planning model, which includes 27,743 links, 10,505 nodes, and 2,191 TAZs. The simulation model contained 162 TAZ nodes and 39 external stations through which the simulation network was connected with the rest of the MWCOG model. A gradient projection (GP) path-based assignment algorithm (Chen et al., 2002) was employed to estimate the static OD demand.

Calibration of the model was then performed by employing the field observation traffic counts provided by SHA in order to test the reliability of the simulation model results. The total counts from 62 stations (red points in figure 38) located on both freeways and arterial roads were employed in the calibration of the simulation model. This microscopic simulation model was validated by comparing the simulated travel times and the observed travel time data collected on major arterial corridors.

After 10 rounds of calibration, the simulated traffic counts and corridor travel times matched the ground truth observations with very high accuracy. Figure 39 presents the scatter plot for the PM peak period (4-7 pm). The points conform to the diagonal line, which indicates that the simulated counts match the field observation counts with high accuracy (consult Zhang et al. 2013 for the details about calibration and validation).

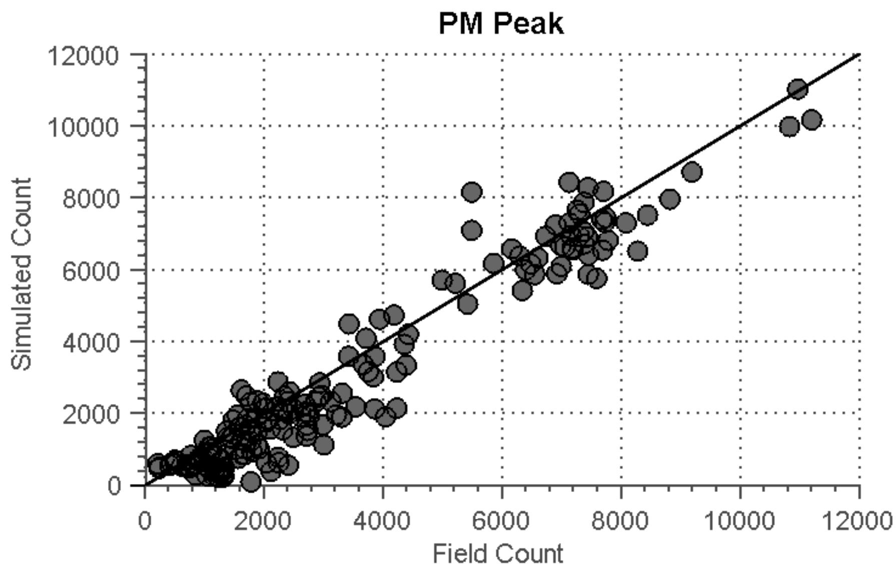



**Figure 39. Scatterplot of Field and Simulated P.M. Counts after Calibration.**

**Emission Model for Environmental Impact Analysis**

The EPA's MOVES model was applied as a post-processing model after the microscopic traffic simulation model. MOVES provides an accurate estimate of emissions from mobile sources based on various kinds of user-defined conditions. To develop a more user-friendly model package, MOVES built its own comprehensive database with emission and energy-related information for the entire United States. MOVES was an appropriate package for the analysis as the input data it needs—such as VMT, average speed, etc.—can be directly obtained from the research team's simulation model results.

Designed with different estimation scales, MOVES can make calculations on national/county levels as well as finer levels available for micro emission analysis. In this project, county-level estimation was chosen for emission estimation of the whole study area, because this level estimation could calculate the emission and fuel consumption in one specified area with similar size within a specified period of time. The data needed for county-level estimation were in part obtained from the simulation model.

In addition, data was obtained from the following sources:

- regional temperature and humidity data from weather websites (The Weather Channel)
- fuel formations data from the default database in MOVES that contains a comprehensive view of category and ingredient
- vehicle age distribution and population data obtained from the 2007-2008 TPB/BMC Household Travel Survey, where all-day number of trips from the simulation model, trip production per household, and number of vehicles per household were used to estimate population
- total VMT, obtained directly from simulation results
- the ratios of different road types obtained from the road attributes in the simulation model
- the ratio of different vehicle types obtained from simulation O-D matrices, which includes O-D matrices of single occupancy vehicle (SOV), high occupancy vehicle (HOV), and trucks
- average speed distribution calculated from the simulated average speeds and simulated sensor count for every segment

After loading these data into the database, the MOVES model was run to calculate gas pollution, solid pollution, and energy consumption within the whole network and the corresponding time scale.

**Model Results and Discussion**

With the combination of trip generation, traffic simulation, and emission estimation models, a before-and after-study was conducted to quantitatively answer the “what-if” questions for TOD developments in Washington, D.C. metropolitan area. As mentioned above, based on the trip generation model results, the OD demand (originally extracted from the MWCOG regional planning model) was modified to reflect the travel demand changes in TOD zones. Then, before-TOD scenario (Base case) as well as an after-TOD scenario (TOD case) were developed. Quantitative measures for the impacts of TOD was then simulated for the PM peak hours of the two scenarios. Network-wide traffic statistics as well as link/intersection-level performance measures were analyzed as the measures of effectiveness (MOEs) for the TOD land development scenario. Also, the level of various emissions and energy consumption were estimated in the environmental impact analysis.

The regional-level trip statistics from the simulation results is summarized in table 20. With the development of TOD zones, the number of auto trips during the PM Peak hours would decrease by 6,500 (1.2 percent), which would lead to some 12,500 miles (0.41 percent) reduction in total

VMT. In addition, the reduction of vehicle hours of travel (VHT) and the increase of network average speed also indicate overall better traffic conditions in the TOD scenario.

**Table 20. Summary-Overall System's Performance.**

| | Number of Trips | VMT (mile) | VHT (hrs) | Avg. Speed (mi/hr) |
|---|---|---|---|---|
| Base Case | 542,739 | 3,116,660 | 155,433 | 20.7 |
| TOD | 536,233 | 3,104,012 | 150,968 | 21.3 |
| % Change | -1.2 | -0.41 | -2.87 | 2.9 |

Our results indicate that, for the whole D.C. area, TODs slightly reduce auto usage and mitigate traffic congestion as well as air pollution. For the PM Peak period, TODs decrease total VMT by 12,648 (0.41%), and total delay by 3,959.1 (4.0%). The environmental impact analysis shows that there is 0.50 percent less GHG emissions and energy consumption in TOD areas. The traffic performance around TOD areas indicates a significant improvement in the TOD scenario. The delay of trips departing from TOD zones decreases by 20.05 percent. Moreover, microscopic traffic simulation model results show a better level of service (LOS) and less congested intersections in the areas surrounding TODs.

With vehicle-level trips data recorded, the total hours of delay as well as the average delay (per trip) in the whole system were obtained for congestion analysis both on the network level and individual level. Based on the delay statistics presented in table 21, the system performance indicated a 3,959.1 hour (2.83%) decrease of total delay in the TOD scenario compared to the base case. Based on a value-of-travel-time-savings (VTTS) estimation for the study area (for average commuter and personal trips, 11.1 $/hour, Xiong et al., 2013), under the TOD scenario, the total travel time savings for the study area are equivalent to $43,946 for one typical PM Peak period. While the difference of network-wide delay per trip is seemingly trivial (only 0.31 minute per trip), the TOD scenario actually makes a significant mitigation to the overall congestion level, saving each trip a 2.83% of peak-hour delay time by switching only 1.2% vehicles off the road.

Moreover, as the majority of the TOD zones belong to the most congested links in the network, it cannot be guaranteed that the TOD development policy directly and immediately improves the traffic among these subareas. Thus, the delay statistics of trips departing from TOD TAZs were also considered to investigate the local impact of TOD policies. As shown in table 21, over 75 percent of the total travel time savings were generated from TOD zones. This comparison indicated that the local impact of TOD policies would make up a major part of TOD's impact throughout the entire study area. The delay per trip result presented in Table 21 indicated that while there was small reduction in delay per trip network-wide (-2.83 percent), significantly high reduction in delay per trip was observed for the trips originated from TOD zones (-20.05 percent).

**Table 21. TOD Travel Time Savings based on Simulation.**

| | Base Case Scenario | TOD Scenario | Travel Time Savings | % Change |
|---|---|---|---|---|
| Network-wide Trip Statistics: | | | | |
| Total Delay(hrs) | 98,943.90 | 94,984.80 | 3,959.10 | -4.00 |
| Delay/Trip (min) | 10.94 | 10.63 | 0.31 | -2.83 |
| Trips from TOD TAZs: | | | | |
| Total Delay(hrs) | 8,520.94 | 5,550.92 | 2,970.02 | -34.86 |
| Delay/Trip (min) | 16.01 | 12.80 | 3.21 | -20.05 |

Although the impact of 12 TOD zones on the whole study area is minor, a noticeable travel time savings of 3.21 minutes per trip during the PM Peak is a significant benefit for TOD areas. In order to obtain a better understanding of the local impact of TODs, the LOS of the key arterials neighboring the TOD zones were estimated. The LOS is a measure that grades the corridor traffic condition comprehensively; information such as vehicle mobility and driver psychological comfort can be reflected in LOS. As an example, figure 40 presents the LOS maps of the major links near west Bethesda and White Flint, two TOD zones with high employment densities. As it shows, the eastbound traffic condition on several segments of Montrose Parkway and Executive Boulevard—two major arterials crossing the area—can be significantly improved in the TOD scenario.

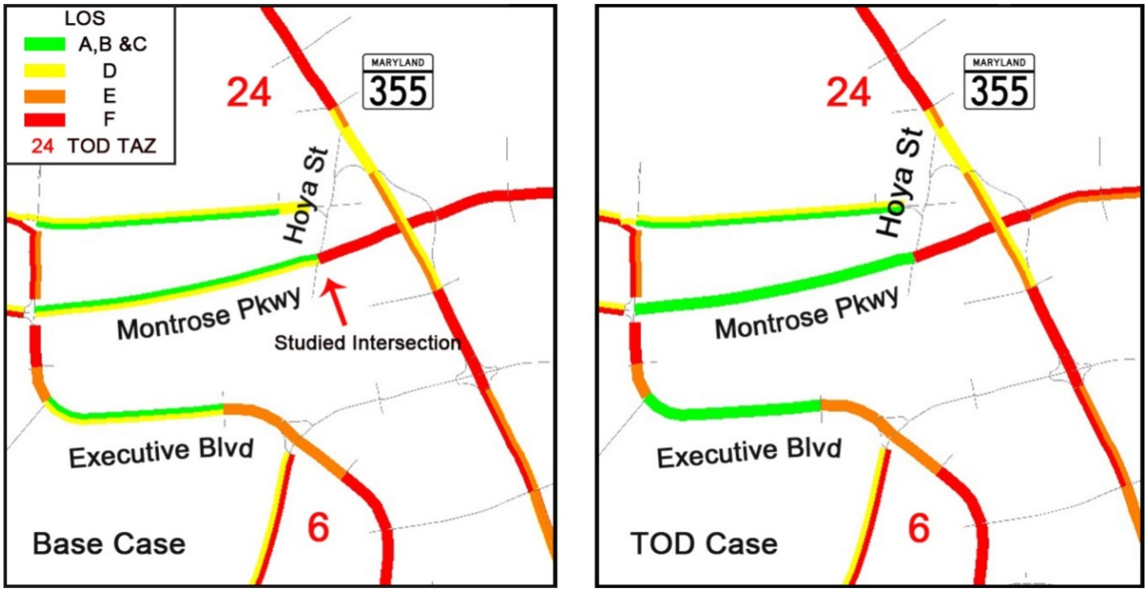
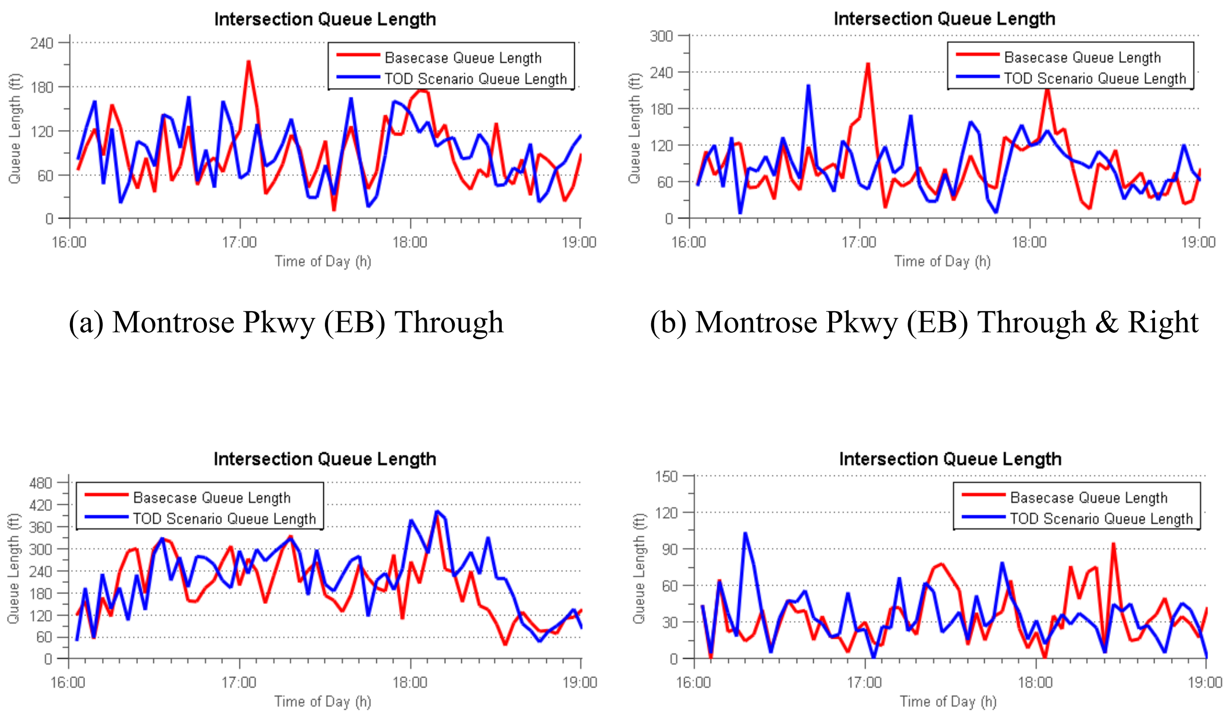



**Figure 40. Level of Service (LOS)[4] of the Network around TOD Zones 6 and 24.**

To evaluate the effect of TOD on microscopic traffic conditions, queue-length analysis for one intersection (Montrose Parkway and Hoya Street) has been provided. The studied intersection (as highlighted by the arrow in figure 40) is selected to highlight the significant changes in traffic delays and queue length (see figure 41 below). At this intersection, the queues for the through and right turn movement on eastbound (EB) Montrose Parkway are shown to be effectively reduced in the TOD scenario. The simulation shows a 10.6-feet (18.7%) decrease in average queue length, which is consistent with the LOS map results. In the right side of the intersection, results show that the average queue length decreases by 2.6 feet (2.4%).

[4] LOS A, B, and C are free and stable flow; D is an indicator of approaching unstable flow due to volume increase; E means the flow is operating at capacity; and F suggests a breakdown flow.




(a) Montrose Pkwy (EB) Through

(b) Montrose Pkwy (EB) Through & Right

(c) Montrose Pkwy (WB) Through

(d) Montrose Pkwy (WB) Through & Right

**Figure 41. Intersection-level Queue Length Dynamics.**

The percentage reduction for various environmental emission types has been presented in table 22 below. These results show that, in general, transit-oriented planning and development is very influential in terms of emissions reduction and the amount of pollutants generated from automobiles in the whole study area. Comparing the amount of various pollutants in the base case and TOD scenario, it is indicated that all types of pollutants—GHG and poisonous emissions—in TODs are lower than that in the base case. The highest rate of reduction belongs to ammonia ($NH_3$), which has a 0.57 percent reduction.

Total energy consumption—petrol and fossil—has also been reduced in TODs by 0.52 percent, which is relatively significant given the scale of the simulated network and relatively few TOD zones as opposed to the base case scenario (non-TOD).

**Table 22. Emission Estimation with EPA MOVES Model.**

| **Time Period: 4:00-7:00 PM** | | | |
|---|---|---|---|
| | Base Case | TOD | % Change |
| **GHG emissions (Gram):** | | | |
| $NH_3$ | 82,193 | 81,726 | -0.57 |
| $CO_2$ | 1,058,830,887 | 1,053,332,141 | -0.52 |
| $CH_4$ | 94,345 | 94,273 | -0.08 |
| $NO_x$ | 1,643,964 | 1,638,916 | -0.31 |
| **Poisonous emissions (Gram):** | | | |
| CO | 29,491,088 | 29,445,104 | -0.16 |
| SO2 | 20,571 | 20,464 | -0.52 |
| **Particulate matter (PM) contamination (Gram):** | | | |
| Total_PM10 | 76,064 | 75,791 | -0.36 |
| Total_PM25 | 70,102 | 69,869 | -0.36 |
| **Energy consumption (Kilo Joule)** | | | |
| Petrol Energy | 14,000,385,596 | 13,927,653,872 | -0.52 |
| Fossil Energy | 14,730,765,884 | 14,654,234,352 | -0.52 |

In summary, the findings from the traffic delay/congestion analysis and environmental impact model are consistent and show that the TOD pattern is associated with an overall lower level of household VMT, fewer travel delays, and a lower level of environmental impacts. However, these effects are more significant in the local surrounding links than in the whole study area.

At first glance, the VMT and travel delay reduction percentages, as well as the environmental impacts, are seemingly trivial to the audience. However, it is worth noting that TODs only remove 1.2 percent of the vehicles off the road, but reduce 2.83 percent of the peak-hour travel delay. Being a highly nonlinear phenomenon when reaching a certain capacity threshold, peak-hour traffic conditions can be significantly improved if the land-use policies reduce the demand even somewhat. The microscopic traffic simulation model restricts the link volume/capacity ratio and thus realistically reflects the impacts of the studied policies, especially for the two peak-hour period.

## CONCLUSIONS

In this research, the research team developed statistical models to analyze the relationship between transit-oriented, high-density development and travel behavior, such as the amount of driving (VMT) and mode choice (at household and trip levels), in two metro areas of Washington, D.C., and Baltimore based on observed data. These models employ different statistical methods, including comparative analysis, hypothesis testing, multiple regression, fixed- and random-effect methods, and environmental impact analysis.

In order to estimate these various models, a number of data sources were employed in this research, including the most recent Household Travel Survey data, land-use data with geocoded population and employment information at the TAZ level, geocoded rail transit stations data, Census block and TAZ shapefiles, and the MSTM model. The research team also developed several innovative data processing, geo-coding, merging, and enhancement tools to combine the aforementioned datasets for this research project.

The findings from the two case studies and statistical models are consistent, and show that transit-oriented land-use planning is associated with an overall lower level of household VMT, increased transit ridership, and reduced traffic congestion and environmental impacts. The VMT model shows that after controlling for several land-use factors, living in TOD areas results in a 20 percent reduction in VMT in the Washington, D.C., area and a 21 percent reduction in Baltimore.

These VMT reduction percentages may appear to be too high, which may be because these models were estimated without controlling for possible self-selection effects. The self-selection effect is a highly debated issue in land use and transportation-related research areas. Researchers argue that reduction in auto ownership and VMT and increased transit ridership in TOD areas, is in part because those who are in favor of transit intentionally choose to move to TOD areas where they can easily access transit. However, it is yet to be determined how large the effect of self-selection is and what methods can be used to measure this effect. In this analysis, the research team did not capture the effect of self-selection due to data limitations. However, socio-demographic variables were included in the models to partly address this issue.

In terms of trip generation rates, results show a higher number of trips generated from TODs in the Baltimore and Washington, D.C., areas. However, when these results are with the findings from the mode share models, a consistent pattern is observed: auto mode share decreases in TOD areas, while share of transit and walk/bike modes increases as a result of living in TOD. This pattern implies that living in a TOD does improve mobility by increasing trip generation rate while promoting the use of sustainable modes and reducing automobile use and VMT.

However, there are some differences in terms of magnitude between the results of the two cases analyzed. In Washington, D.C., the effect of TOD is much higher for both work and non-work trips and results in higher transit ridership and less driving compared to TODs in Baltimore. This is because the transit system in D.C. is more efficient and also because a considerable number of people living in Baltimore commute to Washington, D.C. This portion of the Baltimore population has to drive the distance between their home and work location as there is no transit line connecting downtown Washington, D.C., to Baltimore.

The various models developed in this research may be improved in several aspects in future research. The self-selection effect could be addressed to improve the present VMT model with more sophisticated models. This also requires additional data collection on attitude with the new household travel survey data. There is also room to improve the trip generation and mode share models with more sophisticated modeling methods and statistical approaches.

In summary, the research team believes that programs and policies that are effective in reducing VMT, encouraging transit use, and consequently reducing congestion and pollution in urban areas, such as TOD, should be strengthened. One area that still needs to be examined is parking. A thorough analysis needs to be done on whether parking should be provided in TOD areas and how much parking is needed. Parking is a controversial but important consideration.

With an improved understanding on the relative effectiveness of different policy tools in improving transit ridership and reducing congestion and emissions, policy and decision makers will be able to allocate resources more appropriately and efficiently toward the ultimate goal of making urban areas more sustainable and livable for all residents.

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