ABSTRACT

Title of Thesis: EQUITABLE AND PROGRESSIVE DISTANCE-BASED USER CHARGE:
DESIGN AND EVALUATION OF INCOME-BASED MILEAGE FEES IN MARYLAND

Di Yang, Master of Science, 2014

Directed By: Professor Lei Zhang
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Due to the declining purchasing power of fuel tax revenue, the Highway Trust Fund is insufficient to operate and maintain the surface transportation system in the U.S. Alternative sources of revenue, other than the fuel tax, should be considered to address the insolvency of the funding system. Mileage fees and value pricing have long been attractive options to researchers and decision-makers, but they often raise equity concerns. This paper aims to design and evaluate equitable and progressive distance-based user charge policies, and focuses specifically on income-based fee rate structures. Three variable-rate vehicle-miles traveled (VMT) fee scenarios with respect to income are introduced and all policy scenarios are tested with a statewide transportation model in Maryland. Results show that income-based VMT fees can well protect lower-income households while generating more revenue. However, a standard fee structure based on Ramsey pricing does not work as well as the fixed-percentage incremental fee structure. The latter is progressive across all income groups while ensuring that equity and revenue goals are met.

# EXPLORING PROGRESSIVE VARIABLE-RATE VEHICLE MILEAGE FEE STRUCTURES ON MARYLAND STATEWIDE ROAD NETWORK

By

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# Dedication

I dedicate this thesis to my parents Zeyan Yang and Lingai Wang for their love and care, and my soulmate Jing Du for supporting me all the way.

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# Chapter 1: Introduction

## *1.1 Motivation*

In 2007, the national surface transportation system was placed on the High Risk List by the U.S. Government Accountability Office (GAO, 2013). Several factors contributed to the critical condition of the system; one of the most prominent being the insolvency of its funding sources. The Highway Trust Fund (HTF), which is the main federal funding source for the surface transportation system, receives money primarily from motor fuel and truck-related taxes. However, the federal motor fuel taxes have not increased since 1993 (18.4 cents per gallon for gasoline and 24.4 cents per gallon for diesel fuel) and are now worth 11.5 and 15.2 cents per gallon for gasoline and diesel fuel, respectively, due to inflation. Inflation is not the only reason why the purchasing power of gasoline has declined: restrictive corporate average fuel economy (CAFE) standards and adoption of alternative-fuel vehicles also play a significant role. Despite the funding issues, spending needs have not decreased: in 2012, the Congressional Budget Office estimated that it would cost over $110 billion to maintain the present spending level through 2022 (Puro, 2013). As a result, it is imperative to propose new revenue solutions that are effective, sustainable and equitable.

Researchers and policymakers have been seeking and studying alternative or supplementary policies to overcome the deficiencies of the current funding scheme. In 1995, the National Cooperative Highway Research Program (NCHRP) Report 377 identified and evaluated alternatives to the current status quo, i.e. fuel taxes (Reno

and Stowers, 1995). The report concluded that a fee or tax based on vehicle-miles traveled (VMT) [1] would be a desirable replacement for the motor fuel taxes. There is great flexibility in designing and implementing VMT fees: variable-rate VMT fees can be charged by vehicle type, fuel type, fuel efficiency or even by income to attain different policy goals, such as encouraging the purchase of alternative-fuel vehicles, or vehicles of higher fuel efficiency. Meanwhile, by taxing the level of vehicle-miles traveled rather than fuel consumption, VMT fees should provide a more stable and sustainable revenue stream for the future (Zhang and Lu, 2012).

However, several issues need to be accounted for when developing alternative transportation funding strategies, which include effectiveness, technology, privacy issues, and equity concerns. Equity concerns have captured the attention of politicians and researchers, particularly regarding the effect of the proposed alternative strategies on sensitive groups (Kastrouni et al., 2013). Road pricing often raises equity issues since lower-income drivers are more sensitive to tolls and increased driving cost, hence it is more likely for them to be priced off the road (Sorensen, 2012). Most discussion has focused on flat-rate VMT fees; however, flat-rate VMT fees have been criticized for being regressive, i.e. placing a disproportionate financial burden on lower-income drivers (Zhang et al., 2009). To address these equity concerns, the Transportation Research Board (TRB) has established an expert committee to provide

[1] The transportation field uses several terms interchangeably – "vehicle miles traveled (VMT) fees", "mileage-based user fees", "distance-based fees" and "road-user charges". This paper sticks to the first two.

guidance on assessing the equity of innovative transportation finance mechanisms (NRC, 2011).

### *1.2 Objectives*

The objective of this study is two-fold. First, the author proposes income-based variable-rate VMT fee structures to supplement the resources of the surface transportation system, while ensuring their equitable performance. Variable-rate VMT fees based on household's level of income are proposed, which could address the concern that low-income drivers might be priced off the road. However, one may argue that drivers would not be willing to report their income information due to privacy concerns, which is a major limitation of this income-based fee scheme. To address this issue, the author suggests using household VMT as a proxy for income information as VMT is positively correlated to income (Kastrouni et al., 2014). Using Household Travel Survey data in Baltimore and Washington region, Figure 1 confirms that households with higher level of income tend to drive longer distances. Therefore, using household VMT as a surrogate for income would be a reasonable and feasible approach, since VMT information is readily available via odometer readings.

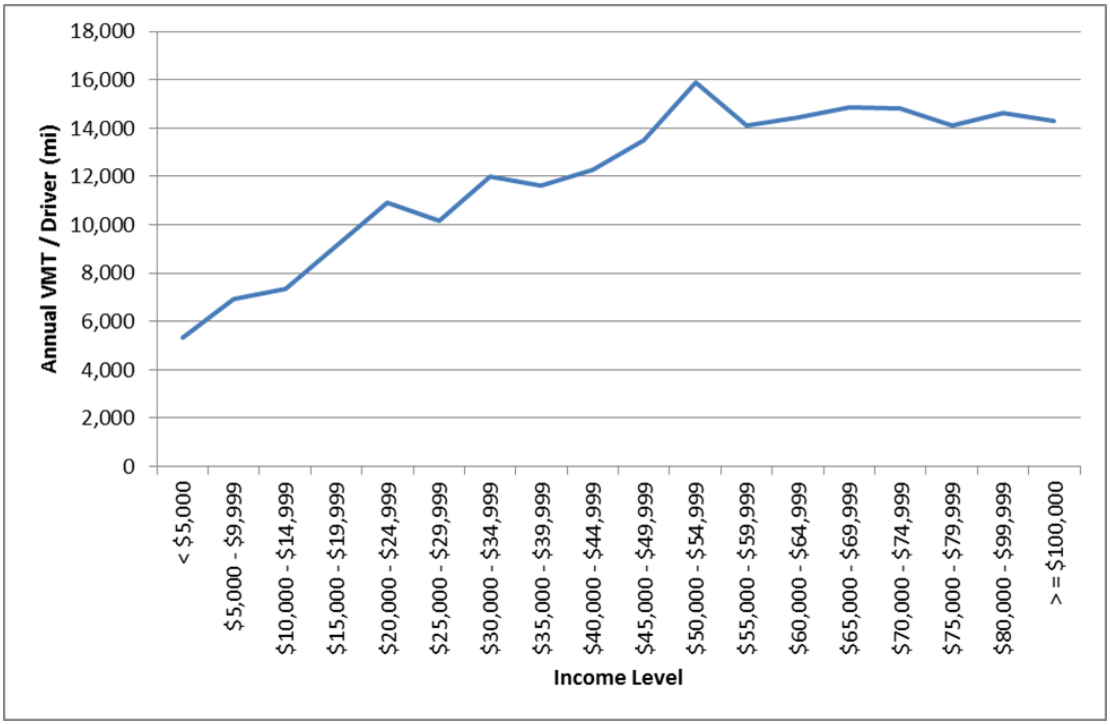


FIGURE 1 Annual VMT (mi) by Income Level

Secondarily, proposed variable-rate VMT fee structures are then applied in a travel demand model to estimate their impacts and effectiveness. Employing the MSTM, the results are generated with geographic information and higher level of detail, which could enhance the decision-making process. To successfully represent a variable-rate VMT fee, the author made an effort to adjust the travel demand model to be able to demonstrate the impacts of such fee structures. This approach for modeling variable-rate VMT fee schemes will hopefully provide researchers with reference in incorporating road pricing schemes in travel demand models.

### *1.3 Contributions*

The major contributions of this thesis are summarized below:

- Proposing variable-rate VMT fee schemes based on drivers' income level in a bid to address the regressivity of the current road pricing strategies, while raising more revenue for the surface transportation system;
- Exploring an alternative approach to model VMT fee schemes: travel demand models are sensitive to road pricing, thus better capture the impacts and effectiveness of the proposed policies;
- Demonstrating the link-level results generated from the travel demand model with high-level geographic information. Via data visualization, results are displayed in a better way to support the decision-making process.

### *1.4 Thesis Outline*

The rest of the thesis is organized as follows.

In Chapter 2, the author first reveals the funding issue of the U.S. surface transportation system. In view of the funding issue, the development of alternative funding schemes is then reviewed with a focus on VMT fee strategies. As part of road pricing policies, user fees are always criticized for raising equity issues, which also leads to the objective of this paper: addressing the equity problem of VMT fee structures. At last, techniques for modeling road pricing strategies are also reviewed in this chapter.

Chapter 3 mainly introduces the modeling tool used in this study, Maryland Statewide Transportation Model (MSTM), and the efforts made to incorporate VMT fee structures in the MSTM. The introduction of the MSTM consists of model overview, model components and data description. And then this chapter highlights that VMT fees should be considered as part of the auto operating cost (AOC) rather

than simply tolls. With this perception, the VMT fee schemes are then incorporated in the destination and mode choice models of the MSTM.

In Chapter 4, four VMT fee structures including one flat-rate and three variable-rate VMT fees are proposed in an attempt to address the equity issue while filling up the surface transportation system's funding gap. The rates of the three variable-rate VMT fees are based on household's level of income and then designed to double the revenue generated under the existing fuel taxes.

In Chapter 5, proposed VMT fee schemes are applied within the study area in the MSTM, as a supplement of the existing gas taxes. Various measures of effectiveness (MOE) are established to estimate different policies' impacts on equity, revenue generation and travel behavior. By comparison, one variable-rate VMT fee structure is recommended by the author, which is overall equitable and effective.

Chapter 6 provides the conclusion to the thesis. Discussions regarding limitations of travel demand models and concerns about the implementation of such income-based VMT fees are also given. At last, suggestions about future research direction are made in this chapter.

# Chapter 2: Literature Review

## *2.1 Funding Issues of the Surface Transportation System in the U.S.*

For a long time, federal and state fuel taxes have been the main source of funding U.S. highway investment and maintenance. In general, fuel taxes are administratively easy to enforce and fairly equitable because it reflects the amount traveled, in other words, those who drive more pay more. However, the fuel taxes are on a cents-per-gallon basis which is economically vulnerable to inflation and improved fuel economy (Sorensen, 2005). Real revenue is difficult to maintain unchanged unless the tax rates are periodically increased, which is politically unpopular. Consequently, the federal fuel tax has been unchanged for 20 years, resulting in a growing deficit for surface transportation projects. According to Congressional Budget Office (CBO), the Congress has transferred $41 billion from the general fund to fill the funding gap ever since 2008. An estimated amount of $110 billion are required to maintain the current spending level plus inflation through 2022, which will actually break the link between highway taxes paid and benefits received by users (Puro, 2013). To address the transportation funding issue, state decision-maker, and even local and regional officials have started to examine a transition from taxing fuel consumptions to taxing vehicle miles of travel within their own jurisdictions. A mileage-based user fee system would offer a significantly more stable source of funding in future decades and could support additional policy goals as well (Sorensen, 2012).

## *2.2 Development of Vehicle Mileage Traveled Fee*

Since Arthur Pigou first introduced the idea of accounting for unpriced traffic externalities in 1920, road pricing has attracted the researchers and policymakers' attention since it can serve both as a travel demand management tool, as well as a tool for revenue generation. Button and Verhoef (1998) provide a comprehensive review on the development of the concept over 75 years and highlighted some of the current practices that are concerned with road pricing issues such as equity, transition from theory to policy and public acceptability.

Mileage-based user fees were first introduced to heavy vehicles over 80,000 pounds, as it was recognized that fuel taxes do not accurately capture all the cost these vehicle impose on the road system (Merriss, 1982). An optimal/ first best pricing should take full marginal cost into consideration which means a driver will pay for all the damage(congestion, pollution, accident risk, etc.) his/her car imposes on the road (Litman, 1999). Compared to variable VMT fees, the first best pricing scheme cannot generate a specific amount of revenue, which is not controllable from an administrative of view. Besides such a user charge is neither technologically feasible nor supported by the public because it is overly complex (Bonsall, 2006). So generally, a simply structured VMT fee would be preferable as it is closer to marginal cost pricing which will result in a more efficient allocation of revenue.

Various studies have been conducted to better understand the impact of VMT fees on travel behavior, revenue generation, equity and environmental preservation. Sorensen and Taylor (2005) reviewed twenty worldwide mileage-based user fee programs including distance-based emission taxes, distance-based user fee proposals and distance-based toll for trucks. DeCorla-Souza (2002) assessed the benefits of

mileage-based vehicle program and estimated that a 20-year stream of benefit at $44 billion would be generated through a nationwide variabilization policy which added 10 cents/mile to the cost of vehicle use. Zhang and McMullen (2008) studied the short- and long-term impacts of VMT fees on income and spatial equity. They found that the distributional effects of a 1.2 cent/mile flat VMT fee are not significant in either the short- or long-term. They also analyzed the distributional impacts of transitioning from a gas tax to a vehicle-mile tax for light vehicles in Oregon, where they found that a flat-rate VMT is slightly more regressive than fuel tax (McMullen and Zhang, 2010). Regarding environmental preservation, Zhang and Methipara (2011) proposed three innovative green transportation funding policies to encourage shifting to vehicles of higher fuel efficiency and reduce greenhouse gas (GHG) emissions. They concluded that the distributional impacts of these three green VMT fee structures are similar to those of the existing gas tax.

Recently, many states have conducted pilot studies to explore the feasibility of a VMT tax for light vehicles. The Oregon legislation formed a Road User Fee Task Force (RUFTF) to recommend alternatives to fuel taxes, and commissioned studies to develop and test the technology. In 2006, Oregon became the first state to implement a pilot study of VMT fee technology (Whitty and Imholt, 2007). Similar pilot studies have since been conducted in various locations including the Minnesota Department of Transportation (Donath, 2003), the Public Policy Center at University of Iowa (Texas Department of Transportation (TxDOT), 2009) and Washington State (Puget Sound Regional Council (PSRC), 2008). To support these pilot studies, emerging technologies allow for more accurate VMT calculation, while ensuring that privacy is

protected, addressing the main issue of the mileage-fee system. Metering options from simple periodic odometer inspections (for instance during annual registration) to on-board units (OBUs) which compute and transmit mileage data electronically, or even smartphone applications, could meet different policy needs (Sorensen et al., 2012). These technical solutions will also ensure the feasibility of this system in the short-run, overcoming infrastructure-related limitations.

### *2.3 Equity Issues with Road Pricing Strategies*

Developing alternative transportation funding options is a complicated task as there are many factors to be accounted for such as privacy, technology reliability and equity. Equity, in particular, is one of the main obstacles for political action and public acceptance (Langhymr, 1997; Oberholzer-Gee, 2002; Ungemah, 2007). In the transportation economics field, TRB identifies five concepts for equity: Benefits Received, Ability to Pay, Return to Source, Costs Imposed, and Participation (NRC, 2011). *"Ability to Pay"* is the main measure of effectiveness (MOE) of equitable performance used in this paper, which is based on the principle that higher-income people should pay more to support public services.

Recent road pricing applications, such as electronic road pricing in Hong Kong and congestion metering in Cambridge, UK, have illustrated the importance of equitable pricing (Ison and Rye, 2005). In vehicle mileage fee designs, road pricing regressivity and progressivity are often used to measure whether a pricing strategy is equitable or not (Levinson, 2010). Both fuel taxes and flat-rate VMT fees are considered regressive as they constitute a larger fraction of income for low-income households than for middle- or high-income households (Poterba, 1991; Zhang et al.,

2009). The distributional impacts of VMT fees among different income groups have been a critical issue in the Oregon mileage-based fee debates (Whitty and Imholt, 2007; Zhang and McMullen, 2008). In order to protect lower-income households (HH) and not to price them off the road, this paper proposes the concept of a variable-rate VMT fee aimed at being progressive with respect to drivers' income, i.e. higher-income households will be charged a higher VMT fee than their lower-income counterparts. This is in accordance with the equity concept of *"Ability-to-Pay"*, proposed by TRB (NRC, 2011).

# Chapter 3: Methodology

The assumption of travel demand models is that travelers make rational choices with respect to destination (trip distribution), transportation mode (mode choice) and route (route choice) (Spear, 2005), in a bid to maximize their utility. When VMT fees are incorporated in travel demand models, driving cost increases: in reaction to this increase, travelers may change destination, mode or route due to changes in their utility. Capturing these travel behavior changes, travel demand models reflect the impacts of the proposed fee structures.

Herein, the author employs the Maryland Statewide Travel Demand Model (MSTM) to analyze the impact of different fee schemes. Compared to past research mainly using regression-based econometric models, this approach is innovative as travel demand models can deal with variables that are not easily quantifiable (such as variables representing values, perceptions and viewpoints) (Zmud, 2005). In addition, results from travel demand models provide higher level of detail by displaying the demand changes at the link-level. With the help of the MSTM, the effects of different policy scenarios on VMT, revenue generation and equity are analyzed in Maryland and its surrounding states of Virginia, Delaware, Pennsylvania and West Virginia.

## *3.1 Maryland Statewide Transportation Model*

Developed by Maryland State Highway Administration, University of Maryland and Parsons Brinkerhoff (PB), the MSTM is a conventional four-step travel demand. The objective of developing the MSTM is twofold: allowing coherent and tenable estimates of how key measures of transportation performance are changed by

different patterns of future development, and contributing to evaluation tools that resolve how future transportation improvements may impact development patterns.

The MSTM works at three levels (regional, statewide and urban level). The scope of this thesis focuses on the statewide level (Figure 2) where 1,588 Statewide Model Zones (SMZs) cover all of Maryland and selected counties in Delaware, Virginia, West Virginia, Pennsylvania, New Jersey and Washington D.C. SMZs are the foundation for MSTM transportation assignment and input land use assumptions. The SMZs exist within counties and are aggregations of Metropolitan Planning Organization (MPO) Traffic Analysis Zones (TAZs).

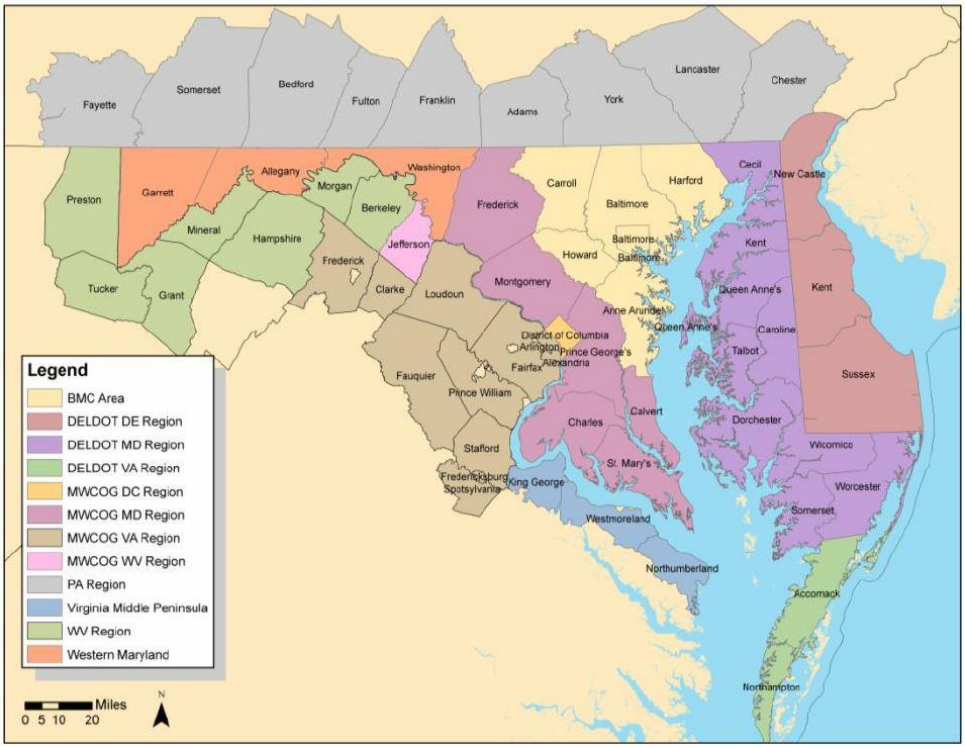


FIGURE 2 MSTM Statewide Level Coverage Map[2]

[2] Maryland Statewide Transportation Model User Guide

3.1.1 Model components

Figure 3 summarizes the MSTM model components within the statewide and regional levels. On the personal travel side, the long-distance travel model for all residents and visitor trips over 50 miles from regional level is combined with statewide level short-distance person trips by study area residents, produced using a trip generation, trip distribution and mode choice components. On the freight side, the regional model estimates the long-distance freight trips into/out of and through the study area, which are combined with short-distance truck trips generated using a trip generation and trip distribution method at the statewide level. At last, the passenger and truck trips from both the regional and statewide model components provide traffic flows allocates to a time period (AM peak, PM peak and off-peak) are input to a single multiclass assignment (MSTM User Guide, 2011).

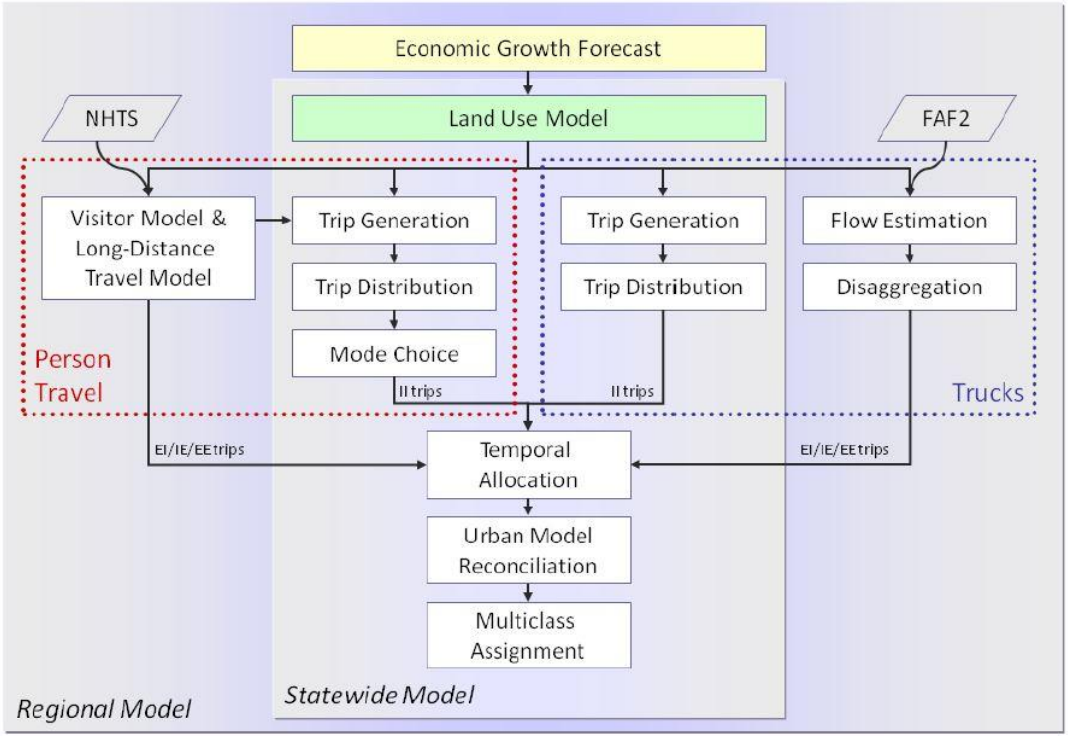


FIGURE 3 Overview of the MSTM model components

3.1.2 Data

The primary input data is from the Household Travel Survey, which was conducted by Transportation Planning Board (TPB) and Baltimore Metropolitan Council (BMC) between May 2007 and Dec 2008. The study area was identified from analysis of the 2000 Based Census Transportation Package (CTP) data to encompass the bulk of labor flows in or out of Maryland. Travel demand data is mainly derived from economic and demographic activities. Census 2000 was used for household socio-economic data, and MPO TAZ data and Quarterly Census Employment and Wages (QCEW) data were used for employment data. Based on the Census data, households within the study area are categorized into five income groups according to the annual income level (in 2000 dollars): *(i)* Lower quintile (≤$20,000), *(ii)* Lower-middle quintile ($20,000-$39,000), (*iii)* Middle quintile ($40,000-$59,000), *(iv)* Upper-middle quintile ($60,000-$99,000) and *(iv)* Upper quintile (≥$100,000). This income categorization allows for incorporating income-based VMT fee structures in MSTM.

*3.2 Incorporating variable-rate VMT fee structure*

Currently, there is no standard approach for representing pricing strategies in travel demand models. How to represent VMT fee structure in the MSTM largely depends on the way that such a fee will be charged in a real-world application. In the Oregon pilot study, tested vehicles were equipped with GPS-based metering equipment, and aggregated billing data were reported when drivers purchased fuel at specially equipped gas stations (Sorensen, 2012). Based on this practice, this study assumes that VMT fees should be treated as part of the auto operating cost (AOC),

which is similar to fuel taxes. Contrary to tolls which are immediately collected from users, VMT fees should be considered as a "long-term" investment, which has less impact on people's travel behavior. Travel demand models assume that travelers choose from a given set of alternatives (choice set) and select the alternative that has the lowest generalized cost (higher utility). In the event of a VMT fee implementation, driving cost increases and travelers either change their mode, or change their destination to shorten the trip distance. However, VMT fees will not influence which route to choose, which is different from the effect of tolls, where travelers will try to switch to alternative routes to avoid tolls. Consequently, the VMT fees do not affect route choice model in MSTM.

### 3.2.1 Mode Choice

MSTM employs a nested logit model for person trip mode choice (Figure 4), which is based on generalized utility functions for auto and transit travel. Generic utility $U_{mi}$ for mode $m$ and income group $i$ is specified as follows:

$$U_{mi} = C_m + \alpha_{1m} IVT_m + \alpha_{2m} TET_m + \alpha_{3m} \frac{Dist_m * AOC_m^i}{VoT^i} + \alpha_{4m} \frac{(PC_m + TC_m)}{VoT^i} + \alpha_{5m} WT_m + \alpha_{6m} NOT_m + \alpha_{7m} TF_m + \alpha_{8m} DAT_m \quad (3.1)$$

where

$C_m$ = constant by mode $m$,

$\alpha_m$ = mode- and attribute-specific coefficient in each term,

$IVT_m$ = in-vehicle time,

$TET_m$ = terminal time,

$Dist_m$ = trip distance,

$AOC_m^i$ = auto operating cost by mode $m$ and income group $i$,

$VoT^i$= value of time by income group $i$,

$PC_m$= parking cost,

$TC_m$ = toll charge,

$WT_m$ = waiting time,

$NOT_m$ = number of transfers,

$TF_m$ = transit fare, and

$DAT_m$ = drive access time.

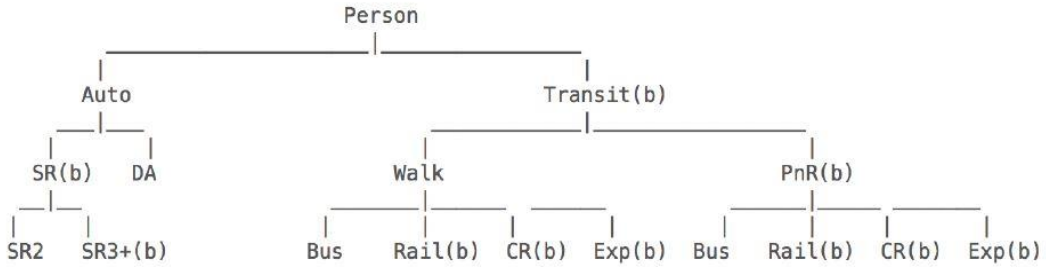


FIGURE 4 Structure of MSTM Mode Choice Model

The Auto Operating Cost (AOC) is part of the utility function used for mode choice, and it varies by mode *m* and income group *i*. The AOC was 9.9 cents/mile (in year 2000 dollars) before the income-based VMT fee is incorporated. About 58% of that cost (5.76 cents/mi) is fuel; the rest (4.14 cents/mi) is maintenance, tires and oil. The fuel component is calculated using a fuel cost of $1.314/gallon and an average on-road fuel efficiency of 22.0 miles/gallon (Davis et al., 2003). Afterwards, the income-based fee is specified for each income group and incorporated into the AOC, so the mode-choice model is sensitive to the variable-rate VMT fee.

Meanwhile, a value of time (VOT) parameter is also added to the utility function, and therefore households with different income levels will respond

differently to the same fee rate. The VOT levels for income groups 1 to 5 are: 8.4, 25, 41.7, 50.4, and 106.4 (cents/mile, in 2000 dollars) respectively. The mode choice model splits origin-destination (O-D) table into three auto modes (single-occupancy vehicles, high-occupancy vehicles with two persons and high-occupancy vehicles with more than two persons), and eight transit modes (walk/drive to bus, express bus, rail and commuter rail).

### 3.2.2 Destination Choice Model

The destination choice model forecasts the probability of choosing any SMZ as the trip end. The model is estimated in a multinomial logit form and the utility $U_{ijn}$ of trip $n$ for purpose $k$ choosing a trip attraction destination $j$ from zone $i$ is given by Equation 3.2.

$$U_{ijn} = S_j + \alpha L_{ij} + \sum \beta^k Z_j^k + \sum \beta^k D_{ij}^k + \sum \beta^k D_{ij}^k N_n^k + C_{jn} \qquad (3.2)$$

where

$S_j$ = size variable for destination zone *j*,

$L_{ij}$ = mode choice logsum between zone pair *i-j*,

$\beta^k$ = weights for each term in size variable,

$Z_j^k$ = attraction zone characteristics (other than size term),

$D_{ij}^k$ = various distance terms,

$N_n^k$ = person, household or production zone characteristics for trip *n* and is used for creating interaction variables with distance term, and

$C_{jn}$ = correction term to compensate for sampling error in model estimation.

In the destination choice model, mode choice logsum ( $L_{ij}$ ) essentially represents the overall accessibility between zone pair *i-j* by all kinds of travel modes. When the VMT fee is implemented and driving cost increases, the mode choice logsum for the zone pair drops, and therefore zone *j* is now less accessible from zone *i*. The destination choice mode provides O-D demand for all trip purposes (Home-Based Work, Home-Based Shopping, Home-Based Others, None Home-Based Work and Other-Based Others).

*3.3 limitations*

However, the traditional four-step travel demand models have certain limitations that need to be acknowledged when analyzing pricing scenarios and discussing the analysis results. First, these models fail to capture the long-term effects of pricing policies on urban land use patterns. Specifically in this study, MSTM only captures travelers' short-term response to changes in driving cost but does account for long-term firm and residential relocation decisions as a result of the VMT implementation. This could potentially lead to overestimation of the VMT generated in the study area under the assumption that land use patterns are fixed. People's long-term response to road pricing has been extensively studied in urban economic theory , from the early monocentric models of Alonso (1964) and Muth (1969) to the latest polycentric models of Anas and Kim (1996), Anas and Xu (1999), and Anas and Rhee (2006, 2007). These pieces of research work explicitly discuss the impact of endogenous congestion and second-best congestion tolls on urban land use in the context of general equilibrium modeling. In recognition of this limitation, researchers propose integrating detailed land use simulation models with travel demand models to

capture the spatial reallocation of firms and households in response to different road pricing policies (Sothworth, 1995; Hunt 2005).

Meanwhile, limitations also lie in the four-step travel demand modeling approach because the four-step travel demand methodology was originally proposed to serve transportation planning purposes. The limitations include temporal constraints and flexibility, dynamic route choice behavior, variation in value of time and land use sensitivity. In fact, many of the shortcomings of the conventional four-step travel demand modeling are not solely related to pricing analysis. In recognition of the limitations of the four-step travel demand prediction model, researchers are interested in exploring advanced and innovative models that are able to accurately carry out more complex pricing policies. These policy analysis needs partially contribute to the development of emerging models such as tour-based model, activity-based microsimulation models and dynamic traffic assignment (DTA). With better representation of travel behavior and increasing analysis capability, these sophisticated models are able to model innovate policy like dynamic pricing while improving the result accuracy and fidelity.

Despite the limitations described above, there are still numerous road pricing analyses done using travel demand models in the literature. Agnello and Bandy (2002) reviewed the Maryland Department of Transportation's (MDOT) variable price study performance with a focus on methodology and techniques. Allen (1995) integrated an emission estimation model with traditional travel demand models to study the effects of transport pricing on emissions. Dehghani et al. (2003) developed a mode-choice system for modeling the impacts of tolls for Florida's Turnpike

Enterprise. Modeling the impacts of pricing policies is still largely relying on classical four-step travel demand modeling or minor variations of such procedures (Pendyala, 2006).

# Chapter 4: Policy Scenario Design

As discussed in the introduction, the purpose of this study is to design an equitable variable-rate VMT fee while doubling the current revenue level that fuel taxes achieve. Past researchers have pointed out that a flat-rate VMT fee is still regressive (McMullen and Zhang, 2010). To verify the results of past research, this paper first implements a flat-rate VMT fee (Policy 1). In order to address the regressivity of a flat-rate VMT fee, this paper proposes a series of variable-rate VMT fee policies that aim to reduce the tax incidence of people with lower ability-to-pay, which is inspired by income and property taxes.

According to Puro (2013), since 2008, Congress has transferred $41 billion from the general fund of the Treasury to the HTF just to maintain the current spending levels. It is urgent to propose alternative funding sources to avoid additional transfers which actually break the link between fuel taxes paid and benefits received by users. Therefore in this study, the three fee structures are designed to DOUBLE the revenue generated under the current fuel tax policy, in a bid to help mitigate the funding shortfall, while also ensuring that the three variable VMT fee schemes are mutually comparable (in this paper, the VMT fee schemes are implemented on top of the current federal and state tax for additional revenue generation).

## *4.1 Flat-rate VMT fee*

In this paper, the flat-rate VMT fee is applied as a supplement of the existing fuel taxes for increased revenue generation. The flat-rate VMT fee in this study is calculated based on Equation 4.1.

$$F_f = \frac{GT}{MPG} \tag{4.1}$$

where $F_f$ represents the flat-rate VMT fee (cents/mile), *GT* is Maryland state gas tax at 23.5 cents/gallon and *MPG* represents the 2002 U.S. light vehicle average fuel efficiency at 22.0 miles/gallon (Davis, 2003). The flat-VMT fee is calculated as 1.1 cents/mile. Under this policy, all drivers are charged the same rate regardless of their socio-economic or travel characteristics.

*4.2 Variable-rate VMT fee based on Ramsey pricing*

Ramsey pricing, also known as the "inverse elasticity rule", is a policy rule according to which the price margins should be inversely proportional to demand elasticity of a product or service. In this case, those with a higher willingness-to-pay (WTP) will pay more than those with a lower WTP. Consequently, the profit generated can be maximized while consumer surplus would not be adversely affected. The concept of Ramsey pricing has been widely applied to public policy analysis for taxation and the pricing of public utilities like electricity and various transport services such as post service (Oum, 1988).

In this paper, the Ramsey pricing VMT fee for each income group can be computed following Equation 4.2:

$$\frac{F_i}{F_{i+1}} = \frac{in\varepsilon_i}{in\varepsilon_{i+1}} \tag{4.2}$$

where $1 \leq i \leq 4$, $in\varepsilon_i$ is the inverse of demand elasticity with respect to operating cost. Unlike the following two variable fee structures where the rates for income group 1 are set to 1.1 cents/mile, the minimum rate in Ramsey Pricing is set

to 2.01 cents/mile. Since Ramsey pricing is based on THE demand elasticity of each income group, the minimum rate of 2.01 cents/mile allows us to meet the policy goal, i.e. to double the fuel tax revenues. In this paper, VMT elasticity with respect to operating cost by income group was calculated using the model developed by Zhang and Lu (2012). The income group information and corresponding elasticity for each income category is illustrated in Table 1.

TABLE 1 Income Information and Demand Elasticity

| *Income Group* | *Income Level (in 2000 dollars)* | *Percentage of Whole Population* | *Demand Elasticity* |
|---|---|---|---|
| INC 1 | < 20,000 | 18.61% | -0.98 |
| INC 2 | 20,000 - 39,999 | 23.36% | -0.82 |
| INC 3 | 40,000 - 59,999 | 25.07% | -0.73 |
| INC 4 | 60,000 - 99,999 | 17.53% | -0.65 |
| INC 5 | > 100,000 | 15.42% | -0.52 |

*4.3 Variable-rate VMT fee based on fixed interval increase*

Under this policy design, the rate for each income group is increased by a fixed interval compared to the previous income group. The fixed interval is set at 0.9 cents/mile, and the goal of this policy design is to generate twice the revenue that fuel taxes are currently generating, making this policy comparable to the other variable-rate polices. This policy is simple to design, easy for the public to comprehend and does not require extra socio-economic information of the drivers. The VMT fee rate $F$ for each income group $i$ is estimated based on Equation 4.3, where $1 \leq i \leq 4$ and $F_1$= 1.1 cents/mil.

$$F_{i+1} = F_i + 0.9 \tag{4.3}$$

*4.4 Variable-rate VMT fee based on fixed percentage increase*

In this scheme, each income group experiences a fixed percentage increase in the VMT fee rate compared to the previous income group. Following the same revenue objective of doubling the current fuel tax revenues, the fixed percentage is set at 50%. The VMT fee rate $F$ for each income group $i$ is designed following Equation 4.4, where $1 \leq i \leq 4$ and $F_1$= 1.1 cents/mile:

$$F_{i+1} = F_i \times (1 + 50\%) \tag{4.4}$$

Table 2 summarizes the VMT fee rates for the four different policy scenarios. It should be noted that, the fee rates for the three variable-rate policies are calculated by trial and error, until they generate twice as much as fuel taxes.

TABLE 2 Summary of Policy Fee Structures

| | *Policy 1: Flat VMT Fee* | *Policy 2: Ramsey Pricing* | *Policy 3: 0.9 cpm Interval* | *Policy 4: 50% Increase* |
|---|---|---|---|---|
| INC 1 | 1.1 | 2.01 | 1.1 | 1.1 |
| INC 2 | 1.1 | 2.41 | 2.0 | 1.65 |
| INC 3 | 1.1 | 2.70 | 2.9 | 2.48 |
| INC 4 | 1.1 | 3.03 | 3.8 | 3.71 |
| INC 5 | 1.1 | 3.80 | 4.7 | 5.57 |

Four VMT fee schemes are proposed to be tested in the MSTM including one flat-rate VMT fee and three variable-rate VMT fees. The flat-rate VMT fee policy, which has widely proposed in the literature and implemented in pilot studies, is used as baseline scenario in this study. The other three variable-rate VMT fees are designed to demonstrate how the idea of income-based charge could help eliminate

the regressivity compared to the baseline scenario in the context of equity. The three variable-rate VMT fee schemes consist of the Ramsey pricing policy, which is based on solid economic theory, and two other self-explanatory policies. This fee design is sufficient to learn the properties of income-based VMT charges and answer the research question that how to design the most equitable VMT fee policy under a specific revenue objective. The four VMT fee schemes are later fed into the MSTM to quantitatively measure their impact on travelers in Maryland.

# Chapter 5: Results

Different policy scenarios are applied within the study area (statewide level) in the MSTM, as a supplement of the existing gas tax. To understand how these policies will affect the economics and people's travel pattern, various measures of effectiveness (MOE) are established to estimate their impacts on revenue generation, equity and travel behavior.

This chapter first examines the distributional impacts of proposed fee schemes by looking at the changes in consumer surplus as percentage of income, which is widely recognized to reflect the fee incidence on people, to measure the equitable performance of proposed policies. The author then explores the effectiveness of proposed fee schemes in generating more revenue. Thanks to the travel demand model which produces results at link level, we are able to obtain the spatial distribution of revenue changes at county level in Maryland. This allows us to understand the financial impacts of proposed policies graphically, which cannot be achieved using statistical models. At last, the changes in VMT are reviewed to estimate policies' effects on travel behavior.

## *5.1 Distributional Impacts*

To measure the distributional impacts, the author estimates the change in consumer surplus (CS) as a percentage of income. Consumer surplus is defined as the difference between the price a consumer pays for an item and the price the consumer would be willing to pay, which measures the level of consumer satisfaction. An increase in driving cost will lead to a reduction in drivers' consumer surplus.

Change in consumer surplus as percentage of income in this study measures the degree of different fee structures' impacts on people's ability-to-pay. In this study, the change in consumer surplus ($\Delta CS$) is computed following the "Rule of the Half" method. The "Rule of the Half" method assumes that the demand curve is linear and consumer surplus is the area of triangle bounded by horizontal line P = $P_{scenario}$ (P denotes price), vertical line D = 0 (D denotes demand) and the demand curve. When the cost changes, the change in consumer surplus is the area of trapezoid with 1) height equal to the change in price and 2) mid-segment length equal to the average of ex-post and ex-ante equilibrium demand. In this study, the change in consumer surplus is calculated using Equation 5.1:

$$\Delta CS = 0.5 \times (M_{gas} + M_{VMT}) \times (F_{gas} - F_{VMT}) \quad (5.1)$$

where $M_{gas}$ and $M_{VMT}$ denote the vehicle mileage before and after implementing the VMT fee, and $F_{gas}$ and $F_{VMT}$ represent fuel cost before and after implementing the VMT fee. Since VMT fees are implemented on top of the current fuel taxes, consumers are expected to experience a reduction in their consumer surplus.

As shown in Figure 5, changes in consumer surplus as percentage of income measure the burden of the VMT charge. A horizontal line in the figure represents perfect fairness where the VMT fee places the same burden across different income groups, which is desirable in this study. On the Y-axis, median income for each income group is employed for the calculation. Figure 5 confirms that a flat-rate VMT fee is regressive across all income groups. The Ramsey pricing scenario, which

reflects the market price and demand elasticity, is slightly less regressive than the flat-VMT fee policy but still imposes a heavier load on lower income groups. This is because differences of demand elasticity across income groups are not large enough. The 0.9 cent/mile interval policy is progressive for lower-income households, but becomes regressive among households of higher ability-to-pay. Only the 50% increase policy performs in an overall "fair" way and can be viewed as progressive.

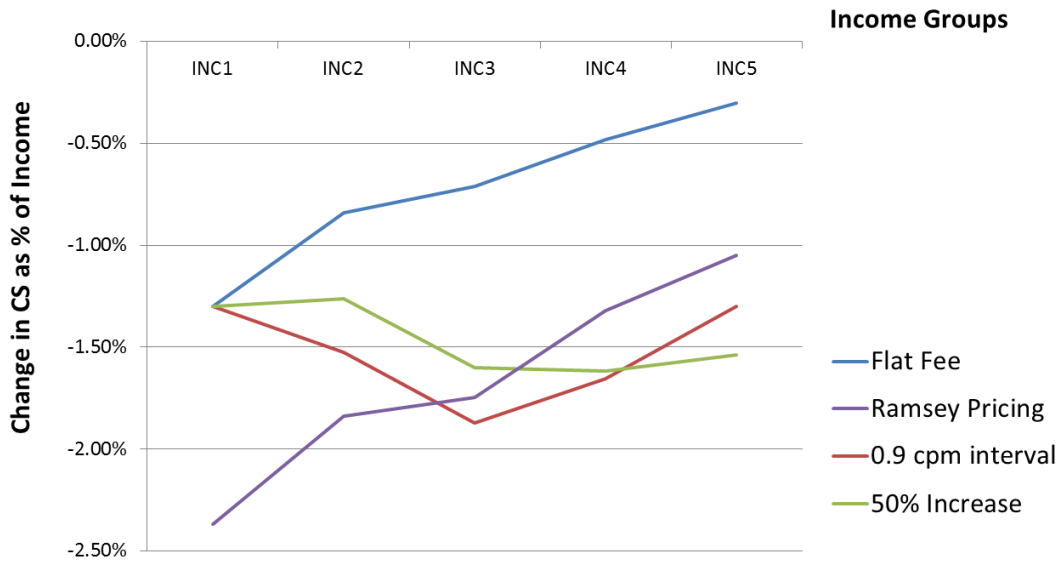


FIGURE 5 Distributional Impacts by Income Group

*5.2 Revenue Generation*

It is vital to assess these proposed policies not only from the consumer's but also from the producer's (in this case the government) perspective. Given the previous discussion regarding the surface transportation funding gap, it is essential to know how income-based variable-rate VMT fees perform with respect to revenue generation. Table 3 summarizes the levels of revenue generated under each scenario, in absolute numbers and in comparison with the current fuel tax.

TABLE 3 Changes of Revenue in Maryland

| | *Current Fuel Tax* | *Policy 1: Flat VMT Fee* | *Policy 2: Ramsey pricing* | *Policy 3: 0.9 cpm Interval* | *Policy 4: 50% Increase* |
|---|---|---|---|---|---|
| Revenue (in 2000 $) | 2,977,612 | 4,689,542 | 6,111,337 | 6,168,868 | 6,320,334 |
| Increase | N/A | 57.49% | 105.24% | 107.17% | 112.26% |

As illustrated in Table 3, a flat-rate VMT fee of 1.1 cents/mile generates 57% more revenue than the existing fuel tax does. Regardless of being regressive or not, the flat-rate VMT fee can already help mitigate the fiscal problem, if implemented on top of the current fuel tax.

Based on the discussion above, Policy 4 (50% increase) is considered the most equitable policy while doubling the revenue generated. However, to better understand how the additional revenue is collected, information on the spatial distribution of the revenue collection is useful. Link-level information generated by MSTM can be aggregated into county level based on the link location. Following this approach, Figure 6 shows how each county will be affected under Policy 4: Montgomery, Howard and Calvert County will contribute the most to the additional revenue generated. These three counties are top-ranked in the per capita income list for Maryland. On the other hand, counties with lower per capita income contribute less in the additional revenue generated. It is also notable that counties within the Washington metropolitan area generate more revenue than counties outside this region, even for counties like Prince George's whose per capita income is not top-ranked. This might be due to the fact that people in Washington metropolitan area tend to be commuters who are more auto-dependent and usually have higher mileage.

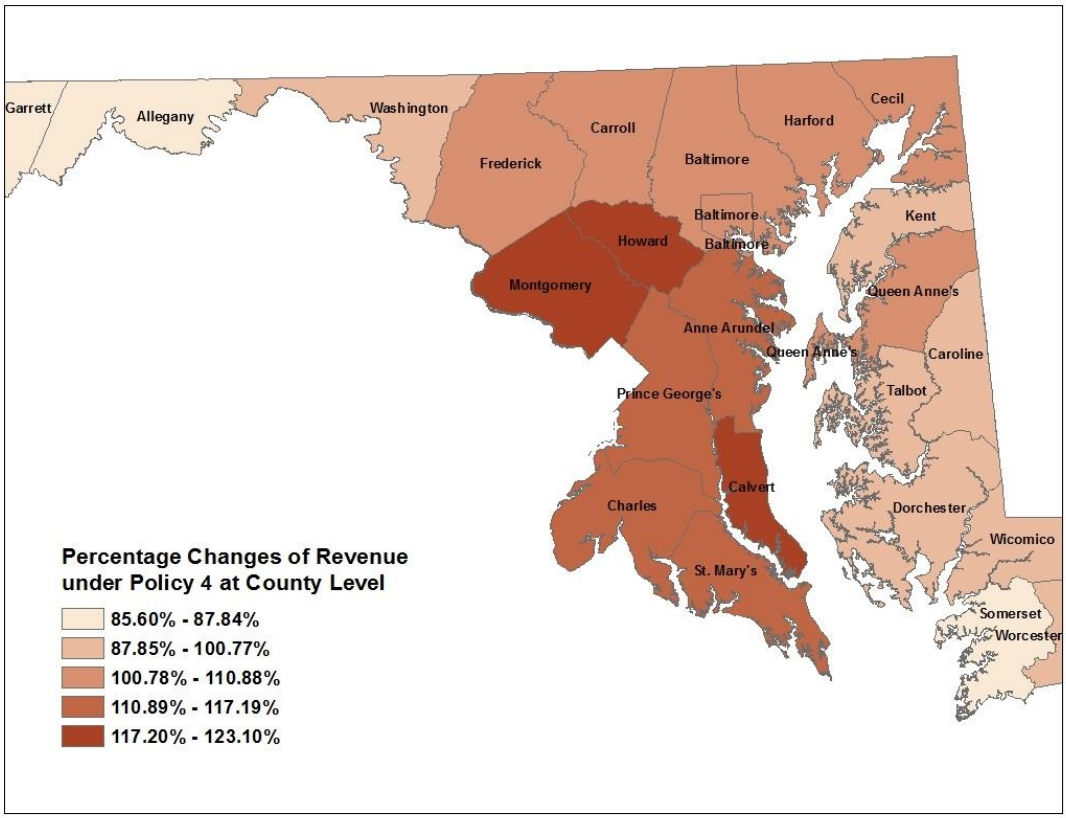


FIGURE 6 Percentage Changes of Revenue in Maryland at County Level

Figure 6 well demonstrates the advantages of employing a travel demand model for this kind of analysis, which allows us to obtain and visualize the results in more detail. However, information with such level of detail cannot be generated using statistical models unless additional geographical knowledge is obtained. With additional information like the spatial distribution of revenue change or VMT change, researchers and politicians can better evaluate different policies and make well-informed decisions.

### *5.3 Travel Behavior*

This section is to explore how people's travel behavior will be affected by VMT fees. Researchers and policymakers have always been concerned that low-

income people will be priced off the road by road pricing strategies. However, Figure 7 demonstrates that the largest decline in VMT that low-income households experience is equal to 2.3% under the Ramsey pricing policy, which is not considered as a significant effect. Figure 7 presents the VMT changes across different income groups within the study area. In general, higher-income households are not as sensitive to variable-rate VMT fee policies as those with lower ability-to-pay. Among the proposed VMT fee schemes, the 0.9 cents/mile interval policy yields the greatest reduction in VMT, followed by the 50% increase policy. It is also interesting to note that the fee rate for people in income group 1 (INC1) is the same under Policy 1, 3 and 4, but Policy 1 (flat-rate VMT fee) has a larger impact on VMT than Policy 3 and 4 (0.9 cpm interval and 50% increase). The reason is that the road network is less congested under the two policies as people from the other four income groups (INC2 – INC5) drive less in Policy 3 and 4, as a result of the increased driving cost. In this sense, lower-income people actually benefit from a variable-rate VMT fee scheme.

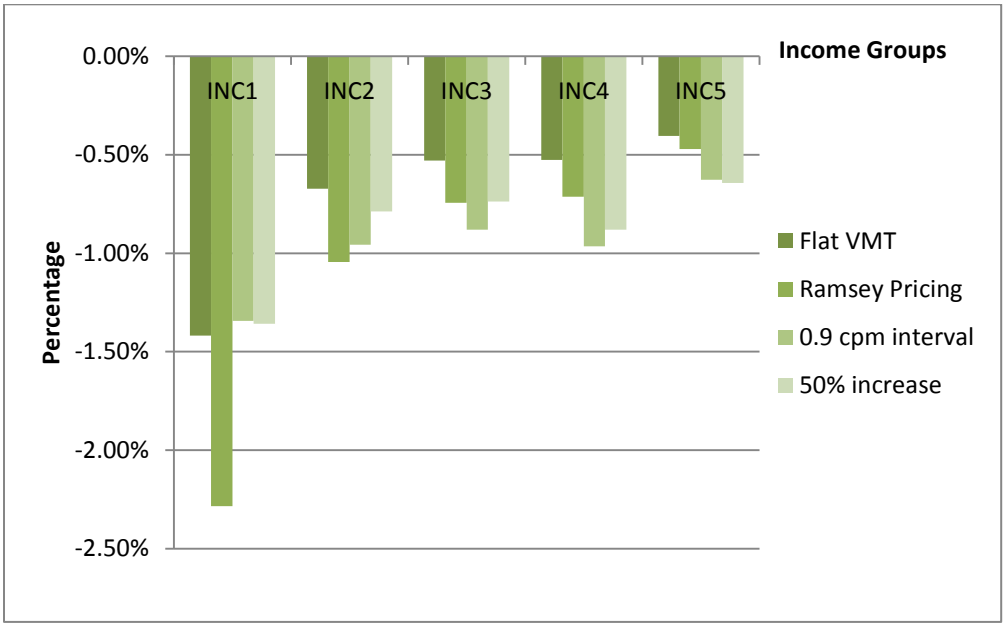

FIGURE 7 Changes in VMT across Income Groups

Figure 8 shows the statewide impacts of the proposed pricing policies in Maryland and its surrounding areas. Results show that all the study areas (Maryland, D.C., Virginia, West Virginia, Delaware and Pennsylvania) experience a similar reduction in VMT, but it should be noted that the overall effects of proposed fees on VMT are not significant. In this study, VMT decline is a result of destination choice mode and mode choice mode being affected by the VMT fees. Due to the increased driving cost, people may either change their trip ends to shorten travel distances or simply switch to non-driving but cheaper modes. Among the four policies, the flat-rate VMT fee structure has the smallest effect on people's VMT while the 0.9 cpm interval and Ramsey pricing policies have a larger impact, which is predictable from the fee structure summary in Table 2.

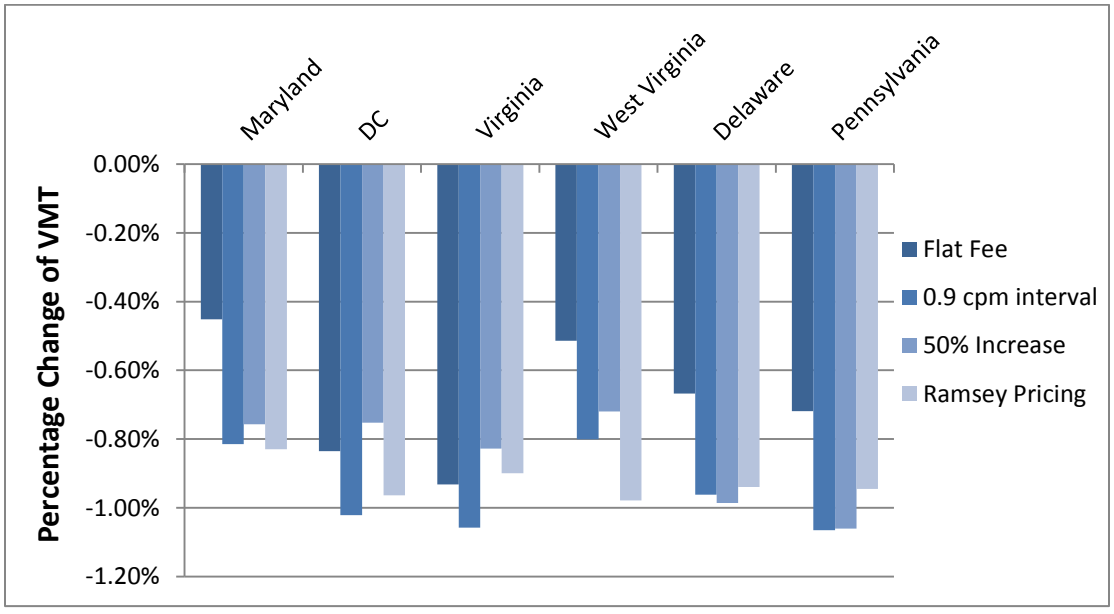


FIGURE 8 Changes in VMT by State

In terms of mode share, driving alone mode for commuter trips decreases after the implementation of VMT fees while carpool and transit users boost. Table 4 shows people's reaction to increasing driving cost in terms of mode choice. We can see from the table that the mode choice impact is expected and not significant, destination choice impact is more profound and there will be winner and loser for various places in the metro area.

TABLE 4 Mode Share for Commuter Trips

| | *Drive Alone* | *Share Ride 2* | *Share Ride 3+* | *Transit* |
|---|---|---|---|---|
| Fuel taxes | 78.01% | 7.68% | 0.21% | 14.10% |
| 50% increase | 77.77% | 7.80% | 0.22% | 14.22% |

Influenced by the policy scenarios, people may change their trip destinations to save driving cost. As a consequence, certain areas would benefit from such policy while other areas suffer in terms of trip attraction. To understand where is considered winner/loser of the policies, Figure 9 illustrates the spatial distribution of changes in trip attraction in D.C. area at Traffic Analysis Zone (TAZ) level. As we can see from the figure that trips to downtown D.C. decrease while more trips arise in residential areas. We can conclude from the result that the increase in driving cost has higher impact to discretionary travel like dinning and recreation. People switch to closer places, which are around the residential areas, for discretionary trips and therefore commercial areas like downtown D.C. become less attractive. However, the impact is not significant in the sense that the largest decline is around 2.00% and the largest increase is around 5.00%.

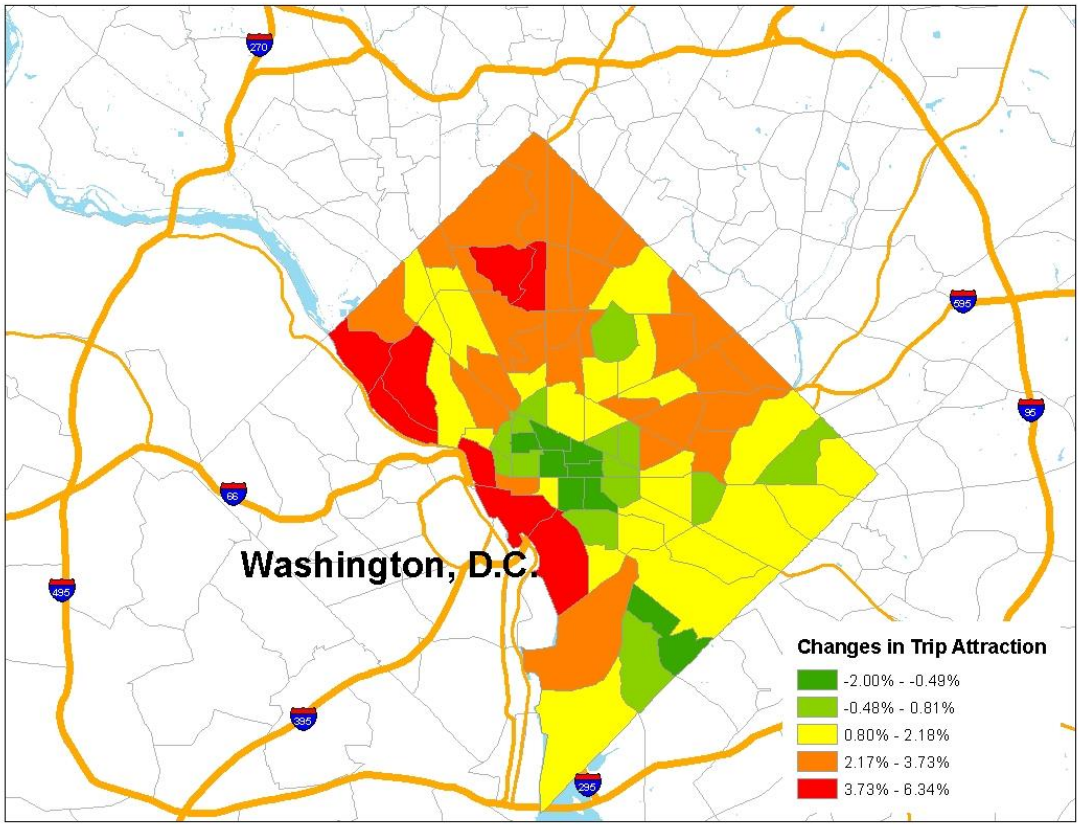


FIGURE 9 Changes in Number of Trips in D.C. after VMT fees

Furthermore, the travel demand model generates more detailed traffic volume results at link level. Figure 10 illustrates the changes in traffic volume under Policy 4. Traffic volume reduction is mainly observed in Maryland and Virginia. It is also interesting to see that links with significant decline in traffic volume are concentrated in urban areas and in facilities like freeways and expressways. This is because freeways and expressways often serve larger traffic volumes than other facility types, resulting in significant traffic volume reduction in absolute numbers. However, even when people are charged with VMT fees, facilities with increased volume can still be observed in Figure 10 (links in orange). This occurs because people may change their trip destinations due to the increased driving cost. In other words, the destination

choice mode in the MSTM is affected by the implementation of the VMT charge. In this sense, few links do experience higher volume as a result of people's trip destination relocation.

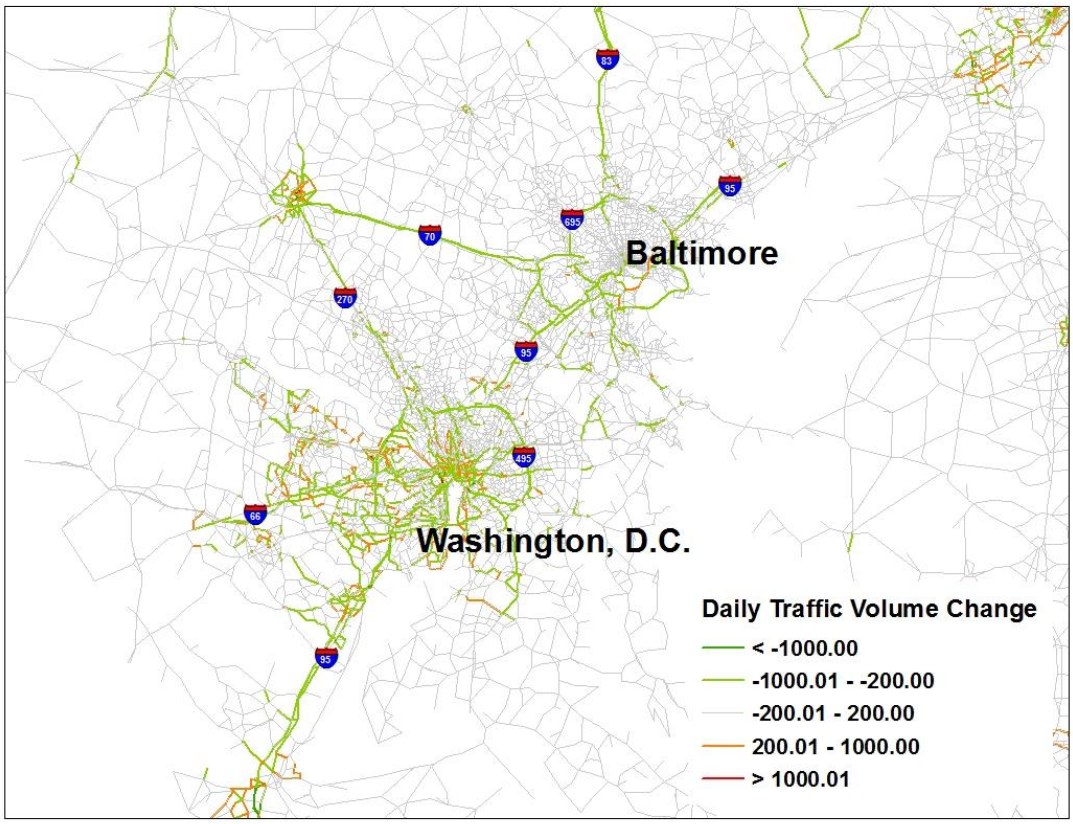


FIGURE 10 Changes in Traffic Volume under 50% Increase Policy

# Chapter 6: Conclusion and Future Direction

## *6.1 Main Findings*

In this study, the Maryland Statewide Transportation Model (MSTM) is employed to quantitatively measure the impacts of four pricing policies: a flat-rate VMT fee, and three income-based variable-rate VMT fee structures. The proposed variable-rate VMT fee schemes aim to address the regressivity of previous fee structures while increasing the revenue generated to supplement the funding gap of the U.S. surface transportation system.

Results show that when the VMT fee rate increases pro rata with people's income, such fee structures would not have a significant impact on people's travel behavior. The average VMT reduction due to the proposed fee schemes is approximately 1% within the study area. On the revenue generation side, VMT fees can supplement the existing fuel tax revenues to mitigate the fiscal deficit. The three income-based VMT fee policies are all designed to double the revenue generated so that they are comparable with respect to their impacts on consumer surplus and travel behavior. Among the proposed fee structures, the policy with a 50% increase rate as people's level of income improves is considered overall progressive. The policy's impacts on revenue generation and travel behavior are estimated at both link and county level: Montgomery, Howard and Calvert counties contribute the most in revenue generation under the 50% increase policy. Results also show that this policy helps decrease the volume on major freeways and expressways.

Developing alternative transportation funding strategies to replace or supplement the current fuel taxes is a complex task needs to account for many concerns. Equity is discussed in this paper but privacy issues are more sensitive in this study, as people might not be willing to report their income information due to privacy considerations, which is a major limitation of income-based VMT fees. To address this issue, the author suggests charging households based on their VMT information, as a proxy for their income. Previous research has indicated the positive correlation between VMT and income level, in other words, richer people tend to drive longer distances (Kastrouni et al., 2014). Therefore, using household VMT as a proxy for income is a reasonable and easy to implement approach, as VMT information is readily available through odometer readings.

### *6.2 Future Research*

Presently, there is no standard approach to incorporate road pricing strategies in travel demand models. This study sheds light on how to implement variable-rate VMT fees in a statewide travel demand model. Future research efforts should focus on improving the sensitivity of travel demand models towards road pricing schemes. Integrating land use simulation models with travel demand models would help researchers and policymakers capture the long-term effects of road pricing policies on land use pattern and understand the spatial reallocation of firms and households in response to such policies.

In theory, the trip generation step in travel demand models should be responsive to changes in road pricing. However, in MSTM, trip generation is not sensitive to VMT fees, as it employs the cross-classification method while a fixed trip

production rate is obtained for each SMZ. This could potentially lead to demand overestimation as the model fails to realize that trip production rates actually drop when travel cost increases. To make trip production rate vary with VMT fees, one could use regression-based analysis at zonal level instead of cross-classification methods. By incorporating a multi-modal accessibility term in the regression model, trip production rate would be sensitive to changes in driving cost. The increase in driving cost indicates higher impact to discretionary travel and more sensitivity found in lower incomes. Future research should make efforts to advance the existing analysis tools or explore new tools to better understand the impact of road pricing schemes, which allows for better and more effective decision-making.

# Appendix A

TABLE 5 Model Specifications

| *Dependent Var: VMT* | *Coefficient* |
|---|---|
| Substitute | -0.0307** |
| *Operatingcost* | *-2.6628*** |
| *Substitute*Operatingcost* | *0.0102*** |
| *lncome* | *-0.1526*** |
| *Operatingcost*Income* | *0.1777*** |
| *Vehicle Count* | *0.8089*** |
| Driver Count | 0.1610** |
| Household Size | 0.0537** |
| Msa_1 | 0.0568** |
| Msa_2 | 0.0154 |
| Msa_3 | -0.0372** |
| Male Respondent | 0.1161** |
| Resp_Age16-34 | 0.3291** |
| Resp_Age35-64 | 0.2610** |
| Resp_America of African | -0.1065** |
| Resp_Asian | -0.1424** |
| Resp_Hispanic | 0.0509 |
| Population Density (1000 persone/square mile) | -0.0281** |
| Constant | 12.0107** |
| R-Square | 0.7692 |

Notes: Italic font indicates the independent variable is logged.

** indicates the variable is significant at 95% confidence interval

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