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ORIGINAL ARTICLE

Declining transportation funding and need for analytical solutions: dynamics and control of VMT tax

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Abstract There is a growing concern among policy makers and analysts regarding the mismatch between demand and supply of the revenue for improving and maintaining highway infrastructure. One possible solution is to link actual vehicle miles traveled (VMT) to the fee structure. The main objective of this paper is to model VMT dynamics and establish a methodology for designing an optimal VMT tax rate. The paper proposes a novel model for VMT dynamics and estimates the model parameters using historical data. An optimal control problem is then formulated by designing a cost function which aims to maximize the generated revenue while keeping the tax rate at a reasonable rate. Using optimal control theory, a solution is provided to this problem. Steady-state analysis of this model is provided and simulations are performed for the 50-year period showing the projected VMT, generated revenue, and the optimal tax rate. The model provides a parameter in the cost function which can be adjusted for achieving a certain amount of revenue in a given time frame.

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Introduction

The United States Highway trust fund, which provides money for highway construction and its maintenance, has been dealing with solvency issues for quite some time. Financial experts and researchers have been debating over alternate funding mechanisms to improve the road revenues and meet the demand side. One of such proposed alternatives is the vehicle miles traveled (VMT)-based road revenue model. In this model, a road usage fee is collected from the user based on the actual miles driven and not based on the amount of fuel purchased. The proposed solution is still in the conceptual stage and much analysis is required in order to establish a proper framework. For example, a thorough of technological challenges and gaps, data-driven modeling, parameter estimation using historical data-sets, and analysis of qualitative and quantitative data to understand the privacy concerns of citizens are needed (Petrescu and Krishen 2017). The advent of big data technologies and availability of abundant data enables researchers to perform interdisciplinary data analytics from marketing and business perspective. These technological advances are particularly very critical in designing a new VMT-based revenue system, as they can provide insights into driving behaviors, sensitivity towards tax rates, privacy concerns, and other key parameters (Krishen and Petrescu 2017).

The current road revenue system in U.S. is mostly based on the fuel tax. The United States Highway Trust Fund is a transportation fund which raises its revenue by levying a federal fuel tax. As of 2014, the federal tax on gasoline is

18.3 cents per gallon and on diesel fuel is 24.4 cents per gallon. The fuel tax-based revenue system has not been able to generate enough revenue to maintain the existing infrastructure (Winston 1991; Wachs 2003). According to various economic studies and projections, revenue generated by the current fuel tax-based system is neither sufficient to add new transportation infrastructure nor to maintain the existing one (Wachs 2005; NSTIFC 2009; Whitty and Imholt 2007). As such, the United States Highway trust fund, which funds the highway construction and their maintenance, has been dealing with solvency issues for quite some time. From 2008 to 2010, the United States Congress sanctioned the transfer of $ 35 billion from the General Fund of the U.S. Treasury to keep the highway trust fund solvent.

As reported by the National Surface Transportation Infrastructure Financing Commission (NSTIF), the U.S. road network grew by only 4.4% in 2009, despite doubling the number of car and truck miles driven on it. Moreover, the federal fuel tax has not changed since 1993 and the federal gasoline tax has experienced a 33% reduction in real purchasing power since that date (NSTIFC 2009; Morris 2006). This over utilization of roads has increased their deterioration rate. Costs associated with the repair and maintenance of road networks are estimated to be increasing at a rate which is three times more than the current funding mechanisms can support. Similar sentiments were shared in a report by the American Association of State Highway and Transportation Officials (AASHTO) in 2007 (NSTPRSC 2007). The report analyzed and predicted future revenue requirements for maintenance of the existing highway systems and for improving transportation infrastructures in the U.S. for the years from 2005 to 2021.

The current road revenue system is based upon the tax associated with the consumption of fuel. In this system, the amount of tax one pays is directly proportional to the amount of fuel consumed. This system is completely insensitive towards the fuel efficiency of a vehicle (Vasudevan and Nambisan 2013b). Vehicles with higher fuel efficiency consume less fuel for the same number of miles driven than ones with lower fuel efficiency, resulting in less revenue. The large differences in fuel economy in current passenger vehicles result in drivers paying widely varying road usage fees per mile depending on their vehicle type. However, the variance in road damage and infrastructure usage is not much different for various types of vehicle weights (Starr McMullen et al. 2010). Additionally, the popularity of fuel-efficient hybrid and non-gasoline powered vehicles and the increasing government mandated fuel economies are anticipated to further adversely affect the collection of road revenues (Vasudevan and Nambisan 2013a).

This over utilization of roadway systems also imposes costly externalities such as congestion delays, pollution, and accidents. In the U.S., approximately 40,000 people are killed every year and many more injured in road accidents. Every such accident has a cost associated with it in terms of insurance, hospitalization, property damage, etc. Similarly, increased congestion results in extended travel time, which in turn negatively impacts productivity. Estimated congestion costs alone ran $ 124 billion in 2013 and are expected to rise to $ 180 billion by 2030 (Delucchi and McCubbin 2010; INRIX 2013). Studies motivated by congestion pricing for road usage-based fee have been performed by (Sumalee et al. 2005; Anas and Lindsey 2011; Kachroo et al. 2017). More vehicles on the roads cause more damage to the environment as well as to the road infrastructure. All of these issues are not taken into consideration in the existing road revenue system.

The historical trend of fuel prices in the U.S. over the years is shown in Fig. 1, and the vehicle miles traveled over the years are shown in Fig. 2. Both these figures show the variability in these variables over the years as economic indicators while the fuel tax has remained relatively constant.

An alternative funding mechanism needs to be formulated in order to address the problems with the existing road revenue system. Many researchers have explored ideas for alternate highway funding such as (Litman 1999; De Palma and Lindsey 2007; Parry and Small 2005; Sorensen and Taylor 2005). Some of these alternatives have been designed to address such major traffic issues as funding and congestion (Fwa 2005; Kirk and Mallett 2013). In particular, various studies have suggested an alternative tax mechanism known as the Vehicle Miles Traveled (VMT) tax (Whitty and Imholt 2007; Litman 1999). The idea behind the mileage based taxation system is that a person pays road tax based on the number of miles actually driven. Researchers believe that this road revenue system would provide adequate highway funding and also reduce the congestion on roads indirectly (Litman 1999). Hence, adjusting VMT charges appropriately during peak-hours will result in reduced road congestion. This might also encourage citizens to use mass transit services, leading to a reduction of total vehicles on the roads.

The concept of distance-based road usage charges is not new for heavy vehicles. It has long been established through research studies that the costs imposed by these vehicles on the roads are not proportional to the amount of revenue paid by them through the fuel tax system (Merriss and Krukar 1982). The damage done to roads generally rises exponentially with weight for heavy vehicles, whereas fuel consumption rises much slower with vehicle weight (Small et al. 1989; Cebon 1999). Countries like Germany, Austria, Slovakia, Poland, Switzerland, Hungary, and New Zealand have already implemented distance-based road usage fees for heavy trucks (Nash et al. 2003; Ecola and Light 2009). Electronic Road Pricing in Hong Kong,

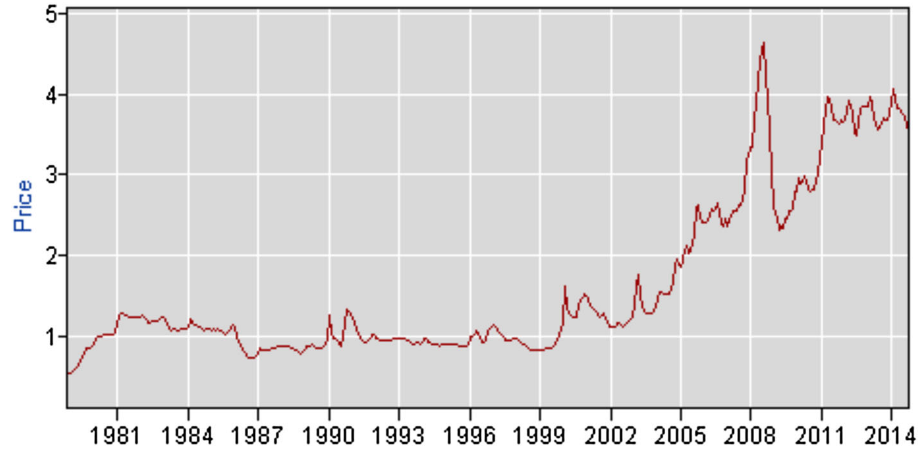


Fig. 1 Fuel prices in $/gallon in the US

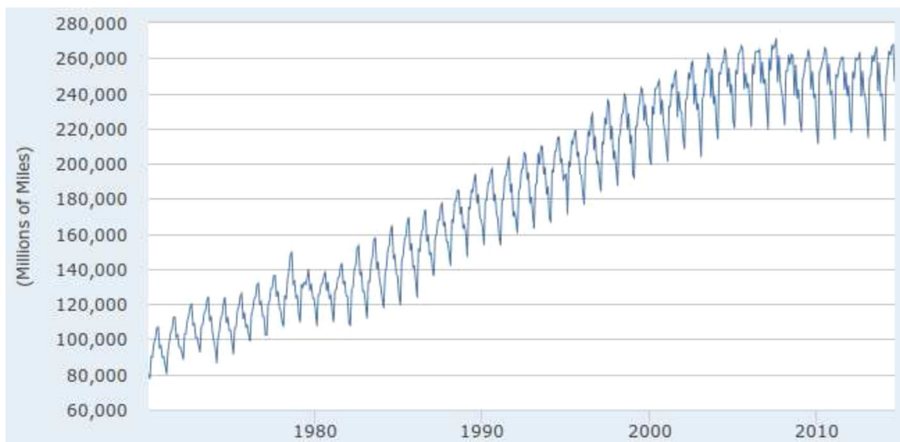


Fig. 2 Vehicle miles traveled in the US

China, and Congestion Metering in some of the cities of UK have also been implemented (Ison and Rye 2005; Hensher and Puckett 2005; Saleh 2005).

In the U.S., Oregon was one of the first states in 2007 to start a pilot project to test the feasibility of this concept. After two phases of successful pilot studies, Oregon is planning to implement this model for a limited pool of 5000 volunteers and keep the tax rate at 1.5 cents per mile. Several other states including Nevada, Iowa, and Minnesota have also followed suit and are in the process of studying the feasibility of VMT-based usage fees.

There are several technological, financial, and individual challenges that need to be resolved before a VMT-based tax system can become a reality. The fee collection mechanism can be designed in many ways. The mechanisms could be very simple registration-like systems where odometer-based reading is used periodically, such as annually. More involved systems could use GPS or smartphone-based systems where a user could be charged less for driving during less congested times. Mechanisms would have to be designed to deal with inter-jurisdictional issues. The idea of usage-based road fees has created a debate among policy makers, economists, and the general public regarding its pros and cons. While the economists and researchers have advocated this idea for quite some time, the general public have many apprehensions about it, such as privacy issues, extra costs in terms of additional technological requirements, and so on (Krishen et al. 2010, 2014a, b; Raschke et al. 2014).

The various aspects of a VMT-based user fee are shown in Fig. 3. The first block refers to the very nature of VMT, which indicates the meaning of the system and its feasibility. Various exploratory studies on this topic can be performed and have been performed. The second block refers to the need for this system. This can be studied by analyzing the funding sources and needs and looking at means to mend the gap between the two. The third block refers to the deployment aspect which involves various technological and non-technological solutions and also mathematical models that can answer questions of rates. The final block refers to the public communication aspect that requires proper marketing using appropriate social theories. This paper addresses the second and third blocks, by providing mathematical models and analysis framework which then addresses the issue of bridging the gap between needs and revenue sources.

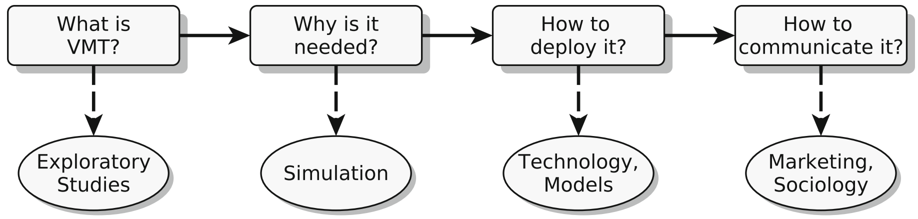


Fig. 3 VMT aspects

It is important to develop and understand a mathematical framework for the VMT-based usage fees. Optimal control theory has been widely applied in various fields of transportation modeling (Selekwa et al. 2003; Hoogendoorn and Bovy 2003; Kachroo et al. 2016), traffic optimization problems (Mahmoud and Eid 1988; Souza et al. 2015; Huang and Yang 1999), and financial optimization (Lin 1987). In this paper, we address the issue of estimating a controlled optimal VMT tax rate which maximizes revenue. For achieving this, a novel model is first proposed for the VMT dynamics and its parameters are estimated based on the historical data. The optimal control problem is then formulated by designing a cost function which aims at maximizing the generated revenue, while keeping the tax rate at a reasonable level. Using optimal control theory, a plausible solution will be provided to this problem. Steady-state analysis of this model is presented and simulations are performed for the next 50 years, showing the projected VMT, generated revenue, and optimal tax rate. The model incorporates a parameter in its cost function which can be adjusted to achieve the desired revenue over a given time frame. The original contributions of this paper to this topic are the development of the dynamic model for VMT, and then designing optimal control strategies that can be used for analysis and policy and rate designs. The paper also uses historical data which are used for the estimation of the parameters of the proposed model. The developed framework helps to design managerial strategies to create and maintain the fee structure in order to keep up with the cost of maintaining, enhancing, and developing the transportation infrastructure for the country. The control strategy can also be designed to integrate with marketing and communication strategies to the public, as the models clearly show why and how the fees are structured for the system.

The remainder of this paper is organized as follows. Section 2 introduces the theory of finding optimal control using the Hamilton–Jacobi–Bellman (HJB) equation. Section 3 formulates the problem statement and proposes a model for VMT. Model parameters are also estimated in the section using the least square estimation technique. Section 4 formulates the optimal control problem for estimation of the VMT tax rate and then provides a solution using optimal control theory. Finally, Sect. 5 provides the simulation results and discussion.

Mathematical background

This section provides a brief mathematical background of the techniques used in modeling the VMT tax rate. The Hamilton–Jacobi–Bellman (HJB) equation is a partial differential equation which forms the basis for optimal control theory. For a given dynamic system and an associated cost function, the solution of the HJB equation is the 'value function' which minimizes/maximizes the cost function (Kirk 2012).

Let the dynamics of the state variable $x(t)$ be given by Eq. (1) as follows

$$\dot{x}(t) = a(x(t), u(t), t)\,, \tag{1}$$

where $u(t)$ is the control variable.

The objective function associated with the system dynamics is given by

$$J = h(x(t_f), t_f) + \int_{t_0}^{t_f} g(x(\tau), u(\tau), \tau)d\tau\,, \tag{2}$$

where t_0 is the initial time and t_f is the final time and h is the terminal benefit at the final time t_f. Function g represents the running benefit. Now for all $t_0 \leq t \leq t_f$ and all admissible $x(t)$, we will try to find the controls that maximize the objective function. The value function is now given by

$$J^*(x(t), t) = \max_{\substack{u(\tau) \\ t \leq \tau \leq t_f}} \left\{ h(x(t_f), t_f) + \int_t^{t_f} g(x(\tau), u(\tau), \tau)d\tau \right\}. \tag{3}$$

A solution to Eq. (3) is obtained by solving the following HJB equation

$$0 = J_t^*(x(t), t) + \max_{u(t)}\{g(x(t), u(t), t) + J_x^{*T} a(x(t), u(t), t)\}\,. \tag{4}$$

We define the Hamiltonian $\mathcal{H}$ as

$$\begin{aligned} &\mathcal{H}(x(t), u(t), J_x^*, t) = g(x(t), u(t), t) + J_x^{*T} a(x(t), u(t), t) \\ &\mathcal{H}(x(t), u^*(x(t), J_x^*, t), J_x^*, t) = \max_{u(t)}\{\mathcal{H}(x(t), u(t), J_x^*, t)\}\,. \end{aligned} \tag{5}$$

then the HJB equation becomes

$$0 = J_t^*(x(t), t) + \mathcal{H}(x(t), u^*(x(t), J_x^*, t), J_x^*, t)\,. \tag{6}$$

The optimal control $u^*(t)$ in terms of J_x^* is obtained from Eq. (5). The value of $u^*(t)$ is then plugged back into Eq. (6) to obtain a PDE in J^*. Solution to this PDE gives the trajectory of the value function J^*. The control law $u^*(t)$ is derived explicitly by plugging J_x^* back into the expression for $u^*(t)$.

Model for VMT

In this section, a mathematical model has been proposed to help in analyzing VMT-based policies and fee structures, as well as in assisting developing pricing strategies. The model is built based on trends of federal and state fuel tax and vehicle miles traveled data over past years.

Problem formulation

Let R_g be the total revenue generated in the current system using a fuel tax. Generated revenue, R_g, can be expressed as $R_g = r_g G$ dollars, where G is the total amount of gas consumed in gallons and r_g is the gas tax rate in dollar/gallons. An interesting point to note here is that the gas tax rate r_g has been relatively constant over the past 10 years, whereas the price of gas (fixed price + tax) has increased significantly. Here, a new system is being studied to collect road usage fee based on the number of miles driven by each vehicle. Thus, Vehicle Miles Traveled (VMT)-based revenue R_v can be estimated based on the number of miles driven by vehicles. The proposed new VMT tax rate is r_v dollars/mile. Hence, the revenue generated based on VMT ($v(t)$) can be estimated as $R_v = r_v v(t)$.

Data from the past few years have information related to monthly and yearly growth of $v(t)$. The number of miles driven at any given time in a basic growth model would increase in proportion to the current VMT due to regular increments in the total number of cars and increments in economic activities. The price of gas (in the case of a fuel tax) or VMT tax rate (in the case of a mileage based taxation) also has a potential impact on VMT based on the fundamental price-demand relationship. If the price of gas (or VMT Tax rate r_v) increases, gas consumption (and the VMT) decreases and if price of gas (or r_v) decreases the consumption of gas (and the VMT) increases. From this discussion, we can present the dynamics of the VMT (number of miles driven) during the time (t_0, t_f) as follows in Eq. (7).

$$\dot{v}(t) = \alpha + Kv(t) - cr(t)\,, \tag{7}$$

where $v(t)$ is the total vehicle miles traveled at time t; $\dot{v}(t)$ is the rate of increment of VMT; α is a constant, K is a positive constant; $r(t) > 0$ is the VMT tax rate; and $c > 0$ is a constant (Verma et al. 2016). Please note that from now on for the sake of notational simplicity, we will denote VMT tax rate $r_v(t)$ by $r(t)$.

Estimation of parameters

Monthly data of nationwide aggregated VMT from years 1993 to 2014 were obtained from the Federal Highway Administration (FHWA). Monthly price trends for fuel rates were obtained from the U.S. Energy Information Administration (USEIA 2012). Figure 4 shows the trend of monthly VMT data and the monthly fuel prices plotted against time.

Parameters K and c have been estimated using the least square estimation technique. Figure 5 shows the linear curve fitting of the data using least square estimation.

If we use the following model for the VMT dynamics as shown in Eq. (8)

$$\dot{v}(t) = \alpha + Kv(t) - cr(t) \tag{8}$$

then the estimated parameters are, $\alpha = -60.02$, $K = 0.29$, and $c = 4.4$. Hence the Eq. (8) becomes

$$\dot{v}(t) = -60.02 + 0.29v(t) - 4.4r(t)\,. \tag{9}$$

Estimation of optimal VMT tax rate

This section provides a complete mathematical framework to estimate the optimal VMT tax rate. The objective of this section is to model R_v based on a model of growth of VMT ($v(t)$), and then to identify the optimal VMT tax rate $r_v(t)$ such that revenue R_v can be maximized, while keeping the tax rate at the minimum level using a weighted combination of revenue and cost.

The VMT-based revenue generated at a given time t can be given as

$$R_v(t) = r(t)v(t)\,.$$

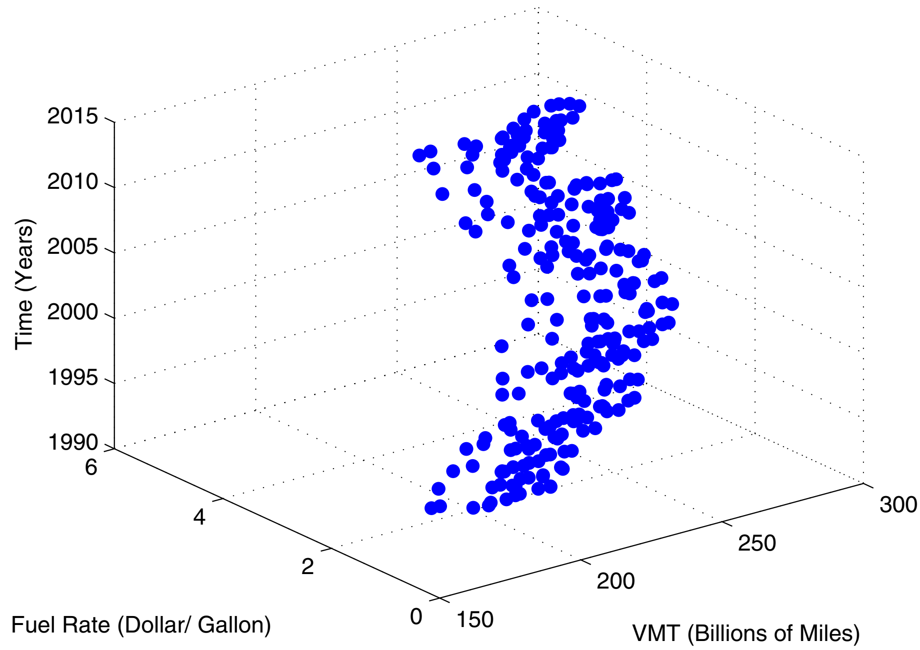
The objective here is to maximize the revenue $R_v(t)$ while minimizing the VMT tax rate $r(t)$ at the same time. Hence we choose a cost function J as shown in Eq. (10)

$$J(t) = \int_t^{t_f} (R_v(\tau) - \epsilon r^2)d\tau\,, \tag{10}$$

or we can write

$$J(t) = \int_t^{t_f} v(\tau)r(\tau)d\tau - \epsilon \int_t^{t_f} r^2 d\tau\,,$$

Fig. 4 Monthly VMT data and fuel prices



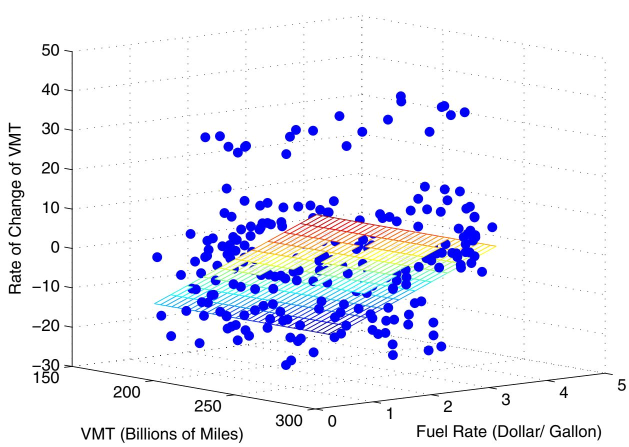


Fig. 5 Least square parameter estimation

where ϵ is a positive constant. The parameter ϵ enables us to fine tune the cost function J in such a way that it produces the desired result in terms of generated revenue or the controlled VMT tax rate. Now the problem transforms into an optimal control problem where the cost function needs to be maximized.

Solution using optimal control theory

In the problem formulation discussed above, $r(t)$ is the control variable and $v(t)$ represents the state variable. Comparing the expressions for $\dot{v}(t)$ and $J(t)$ with Eqs. (1) and (2) we have

$$h(x(t_f, t_f) = 0,$$

$$g(x(t), t, r(t)) = v(t)r(t) - \epsilon r^2(t)$$

and $\quad a(x(t), t, r(t)) = \alpha + Kv - cr(t).$

Hence the Hamilton–Jacobi–Bellman equation can be written as

$$0 = J_t^* + \max_{r(t)}\{v(t)r(t) - \epsilon r^2(t) + J_v^*(\alpha + Kv - cr(t))\}. \tag{11}$$

It can also be written as

$$0 = J_t^* + \mathcal{H}(x(t), r^*(x(t), J_v^*, t), J_v^*, t)$$

where Hamiltonian $\mathcal{H}$ is given by

$$\mathcal{H}(x(t), r^*(x(t), J_v^*, t), J_v^*, t) = \max_{r(t)}\{v(t)r(t) - \epsilon r^2(t) + J_v^*(\alpha + Kv - cr(t))\}. \tag{12}$$

A necessary condition that the optimal control must satisfy is

$$\frac{\partial \mathcal{H}}{\partial r} = 0.$$

Hence differentiating the Hamiltonian with respect to the control variable $r(t)$ we get

$$\frac{\partial \mathcal{H}}{\partial r} = v(t) - 2\epsilon r(t) - cJ_v^* = 0$$

or we can write that

$$r^*(t) = \frac{v(t) - cJ_v^*}{2\epsilon}. \tag{13}$$

We also observe that

$$\frac{\partial^2 \mathcal{H}}{\partial r^2} = -2\epsilon < 0,$$

thus, the control in Eq. (13) maximizes the Hamiltonian $\mathcal{H}$. Now plugging back the value of $r^*(t)$ into HJB Eq. (11) we get

$$0 = J_t^* + v(t)\left(\frac{v(t) - cJ_v^*}{2\epsilon}\right) - \epsilon\left(\frac{v(t) - cJ_v^*}{2\epsilon}\right)^2 + J_v^*\left(\alpha + Kv - c\left(\frac{v(t) - cJ_v^*}{2\epsilon}\right)\right). \quad (14)$$

Further simplification gives

$$0 = J_t^* + \frac{c^2}{4\epsilon}(J_v^*)^2 + \left(\alpha + Kv(t) - \frac{cv(t)}{2\epsilon}\right)J_v^* + \frac{v(t)^2}{4\epsilon}. \quad (15)$$

Equation (15) represents the HJB equation for the optimal control problem. Solving the PDE analytically in Eq. (15) is a non-trivial problem. Numerically, the PDE can be solved for specific boundary conditions. We perform steady-state analysis that enables a feedback solution for a long time horizon. Once function J is identified, the value of J can be plugged back into Eq. (13) to get the control variable. The above HJB equation has been solved using the steady-state analysis in the sections that follow. Parameters K, c, and α have already been estimated based on linear curve fitting of the past VMT data in the previous section.

Steady-state analysis

In steady state, derivatives with respect to time are zero, and consequently, we have

$$J_t^* = 0.$$

Equation (15) becomes quadratic in J_v^* as shown in Eq. (16).

$$0 = \frac{c^2}{4\epsilon}(J_v^*)^2 + v\left(\alpha + K - \frac{c}{2\epsilon}\right)J_v^* + \frac{v^2}{4\epsilon}. \quad (16)$$

For Eq. (16) to have real roots, $b^2 - 4ac \geq 0$. This means that

$$b^2 - 4ac = (v(\alpha + K - c/2\epsilon))^2 - 4(c^2/4\epsilon)v^2/4\epsilon \geq 0.$$

Simplifying further, we get

$$(Kv(t) - cv(t)/2\epsilon + \alpha)^2 \geq (cv(t)/2\epsilon)^2$$

which means

$$Kv(t) - cv(t)/2\epsilon + \alpha \geq cv(t)/2\epsilon$$

or

$$Kv(t) - cv(t)/2\epsilon + \alpha < cv(t)/2\epsilon.$$

Simplifying more, we obtain

$$Kv(t) + \alpha \geq cv(t)/\epsilon \quad \text{or} \quad Kv(t) + \alpha < 0.$$

Therefore, we can write the conditions for the real roots as

$$\epsilon \geq \left(\frac{cv(t)}{Kv(t) + \alpha}\right) \quad \text{or} \quad v(t) < \frac{-\alpha}{K}. \quad (17)$$

Now that Eq. (16) has real roots in steady state, values of J_v^* is given by

$$J_v^* = \frac{M}{c^2/2\epsilon}, \quad (18)$$

where

$$M = -(\alpha + Kv(t) - cv(t)/2\epsilon) \pm \sqrt{(\alpha + Kv(t) - cv(t)/2\epsilon)^2 - c^2v(t)^2/4\epsilon^2}. \quad (19)$$

If we call the two roots of J_v^* as $\gamma_1(v(t))$ and $\gamma_2(v(t))$, then the optimal tax rate can be written as

$$r(t) = \frac{v(t) - c\gamma(v(t))}{2\epsilon}. \quad (20)$$

The optimal VMT tax rate $r(t)$ has been obtained in terms of $v(t)$ for the steady state in Eq. (20). Now using this control variable $r(t)$, the dynamics of VMT $v(t)$ and revenue $R(t)$ can be estimated. Simulation results are provided in the next section.

Simulations, results, and discussion

In the previous section, the function $r(t)$ was formulated in terms of $v(t)$ in steady state (see Eq. (20)). Now we will solve the dynamics of $v(t)$ numerically and obtain corresponding optimal tax rate. These simulations are performed for $\epsilon = .0009$. ϵ serves as a parameter in the model which provides the flexibility to fine tune the optimal tax rate and the corresponding revenue needed. Figure 6 shows the projections of monthly VMT ($v(t)$) for the 50-year period from 2010 to 2060. Figure 7 shows the corresponding optimal tax rate $r(t)$ for the 50-year period.

We can also estimate the monthly revenue based upon the projected values of VMT and the optimal tax rate. The revenue has been projected for 50 years as shown in Fig. 8. Yearly revenue projections are shown in Fig. 9.

To better demonstrate the magnitude and implications of the results presented above, we will break the analysis into short-term and long-term time horizons. Table 1 looks at the near-term needs, revenue forecasts, funding gaps, and

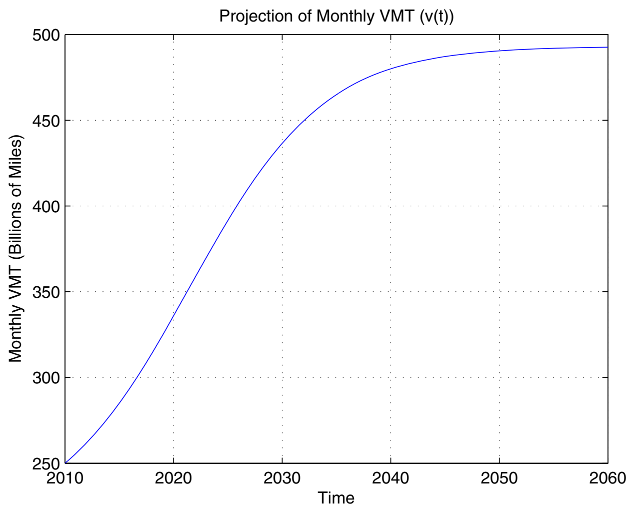


Fig. 6 Projected VMT for 50 years

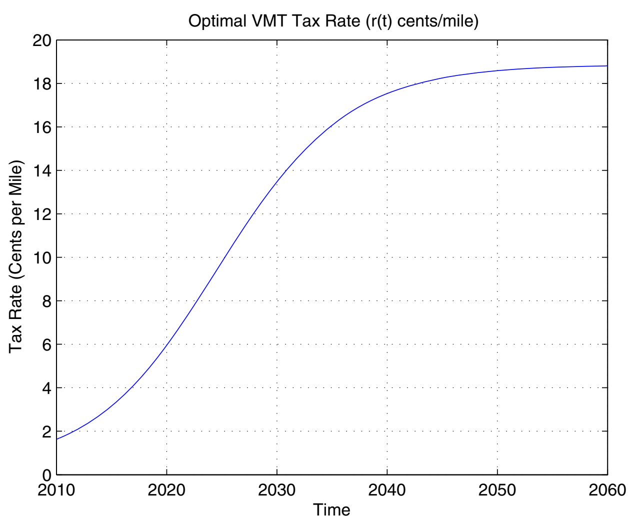


Fig. 7 Optimal tax rate $r(t)$ 50 years

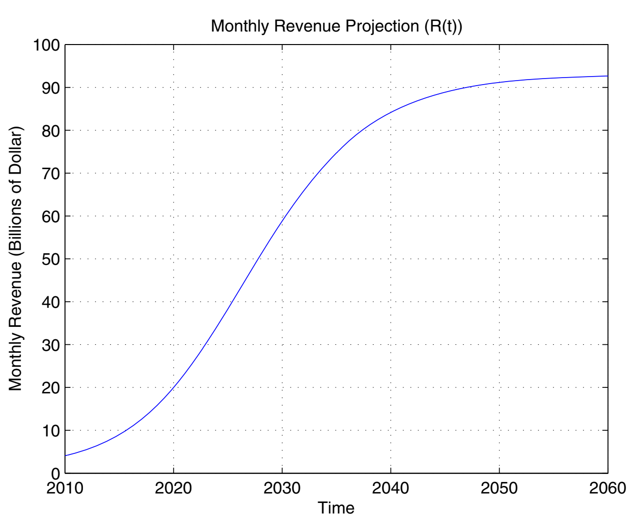


Fig. 8 Projected monthly revenue

also at the estimated optimal VMT tax and the corresponding revenue forecast. As shown in the table, the baseline revenue forecast totals $ 235 billion during 2010–2015 period or an average of $ 39.2 billion per year. Revenue needs and forecasts (from the current system) are obtained from (NSTIFC 2009). The table also presents the revenue forecasts using the VMT tax system which brings down the funding gap from $ 671 Billion to $ 187 Billion.

In the NSTIF commission report in 2009, long-term revenue needs (from 2008 to 2035) were estimated to be $ 386 billion annually, on average (NSTIFC 2009). Hence the cumulative funds required for a 25-year period (2010–2035) would be $ 96,500 billion. Figure 9 shows that using the estimated optimal VMT tax rate, the required cumulative funds are matched in the year 2035. During this period, the estimated optimal VMT tax rate varies between 1.72 cents/mile and 15.84 cents/mile. On average, the tax rate is 8.20 cents per mile for this period. In the report, the required VMT fee to meet the long-term revenue demand was estimated between 7.8 and 8.4 cents per mile. Hence the results obtained in this research are consistent with those provided in the NSTIF report. Moreover, our model can be used for predictions and analysis for future scenarios.

Conclusion

In various studies, VMT-based tax has been proven to be a potential alternative to the current gas tax-based road revenue system. Apart from various technical challenges, it is extremely important to understand the mathematical aspect of the VMT tax model. In order to be sure that VMT will address the gap between required and generated revenue, it is necessary to develop and study mathematical

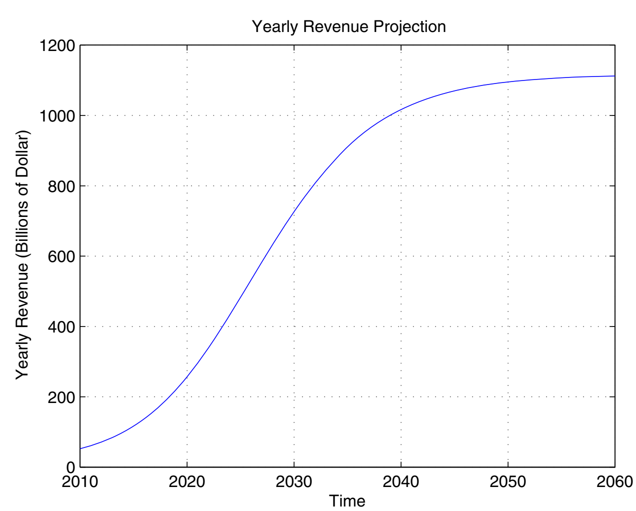


Fig. 9 Projected yearly revenue

Table 1 Short-term needs and revenue forecasts: 2010–2015 (Billions of $)

Year	Revenue needed	Revenue forecast from current system	Optimal VMT tax rate (cents/mile)	Revenue forecast from optimal VMT tax
2010	$181	$38	1.72	$52.4
2011	$184	$38	1.96	$61.1
2012	$188	$39	2.24	$71.5
2013	$192	$40	2.57	$84.0
2014	$195	$40	2.93	$98.9
2015	$200	$40	3.35	$116.56
Total	$1141	$235	–	$671

models considering all possible factors such as economic growth, impact of VMT tax on VMT. This paper dealt with the modeling, estimation, and optimal control of the vehicle miles traveled user fee. While modeling the vehicle miles traveled, the impact of potential changes in the VMT tax rate was considered. An optimal control problem was formulated such that the designed cost function maximized the generated revenue while minimizing the VMT tax rate. Parameters of models were estimated using past data for various years. Once the parameters were estimated, future predictions were made based on current values. Based on the revenue estimates for a variable tax rate, VMT appears to have the potential to address the gap between required and currently generated gas tax revenue. For estimation of the VMT tax rate, the optimal control model of VMT must be further refined to incorporate key factors such as inflation, congestion.

In combination with previous research on VMT, the current paper proposed a model that optimizes the cost function. Although such a usage fee can increase the viability and usefulness of a VMT-generated revenue, the marketing of this policy to citizen consumers is yet another important aspect. As such, several interdisciplinary research studies have uncovered multiple potential public issues, using both qualitative and quantitative techniques. For example, Krishen et al. (2010, 2014a) propose ways in which marketing communications can be framed in order to improve consumer fairness perceptions of a VMT usage fee. Another study analyzes unprompted consumer comments regarding a potential VMT usage fee and identifies privacy and cost allocation concerns as the largest consumer issues (Krishen et al. 2014b). Privacy concerns remain a very important interdisciplinary research topic, especially in regard to the imposing of a VMT usage fee since such a fee could require vehicle tracking devices. To further understand possible apprehension to such concerns, Raschke et al. (2014) delineate four types of consumer concerns and show relative weights for each of them. Augmenting all of this research, the proposed research can aid in the implementation of VMT consumer communication campaigns since this model can show consumers that the VMT fee maximizes and optimizes transportation infrastructure benefits.

As shown in the current research, by imposing a VMT usage fee, road infrastructure can be maintained since the incoming revenue will more readily account for the structural needs. Future research can address the allocation and prioritization of transportation infrastructure projects once the VMT usage fee is imposed as well as examine the cost–benefit analysis of such projects (Shang et al. 2004; Joshi and Lambert 2007). VMT usage fees will not only allow the system to generate sufficient revenue to improve the road infrastructure, but also will provide a transparent and fair tax policy to the citizens.

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