Title
Essays on Tax Policy Assessment Considering Electric Vehicle Growth

Author
CHEON, JI YEON

Publication Date
2023

Peer reviewed|Thesis/dissertation

Essays on Tax Policy Assessment Considering Electric Vehicle Growth

By

JI YEON CHEON
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Agricultural and Resource Economics

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Kevin Novan, Chair

Erich Muehlegger

Aaron Smith

Committee in Charge

2023

Acknowledgments

This endeavor would not have been possible without the invaluable comments and feedback of my main advisors, Kevin Novan and Erich Muehlegger. Their endless questions and vast knowledge guided me through this challenging journey. I would also like to express my deep gratitude to my graduate advisor, Richard Sexton, and my master's chair, Pierre Mérel, who provided guidelines and supported me in undertaking this journey. Additionally, I would like to thank my dissertation committee member, Aaron Smith.

I want to give special thanks to my family. My faithful husband, Hyundo Joo, motivated me to start studying. My lovely children, Aaron Joo and Arene Joo, were born during my Ph.D. and pushed me to make the impossible possible. My mother came to me whenever I needed. My mother-in-law also came a long way to help me. My thanks should also go to my father, sister, brother, and father-in-law for their support, prayers, and understanding of my whole situation.

I am also grateful to my friends and cohorts, especially Sangwon, Seungjin, Sonia, Qian, Jinmahn, and Seunghyun, who helped and encouraged me to continue this process.

Finally, my thanks to God cannot be expressed in words.

Essays on Tax Policy Assessment Considering Electric Vehicle Growth

Abstract

In recent years, electric vehicles (EVs) have continued to grow. According to one forecast, EV share among registered cars will reach about 7% within a decade. The high share of EVs will accelerate the deficit in government revenues from gasoline taxes. Therefore, a vehicle miles traveled (VMT) tax is being discussed as an alternative to the automobile fuel tax. The government is considering the policy shift from a gasoline tax to a VMT tax, that affects almost populations, but few studies have evaluated the new policy while taking into account the growth of EVs. This paper bridges the gap between assessing the VMT tax and considering increasing EV penetration.

Chapter 1 discusses the distributional effect of a VMT tax when considering the penetration of electric vehicles. It studies the impact of a VMT tax introduction on vehicle choice and utilization in a two-period model that links two decisions on vehicle choice and subsequent driving. Also, it examines the consumer surplus changes in the short term due to policy shifts from a gasoline tax to a VMT tax according to vehicle types, fuel economy, and household attributes. The results show that the revenue-neutral VMT tax would increase consumer surplus by a modest $2 per vehicle per year. It also suggests that even if the government imposes the same federal VMT tax rate, each state could be a winner or loser depending on the average MPG, miles driven, and VMT elasticity. Ultimately, the results show that shifting policy towards a VMT tax becomes more efficient as the penetration of EVs grows. When the EV share reaches 5%, the incremental EV share generates an additional surplus equal to twice the surplus from adopting the revenue-neutral VMT tax. It can also reduce revenue and expenditure discrepancies without changing the tax rate.

Chapter 2 explores a VMT tax to increase government revenues as electric vehicle penetration grows and the long-term impact of that tax on consumer surplus. By taking the estimates from the two-period structural model for vehicle choice and utilization, it conducts a counterfactual analysis

to increase government revenue by 30%. Based on the results, the following sensitivity analyses target the cases where government revenue increases from 30% to 100%, and the share of electric vehicles increases from 3% to 10%. As a result, the VMT tax generates a small but positive net consumer surplus compared to the gasoline tax when moderately increasing government revenues. Net consumer surplus from the VMT tax rises incrementally as the growth rate in government tax revenue increases. If the proportion of electric vehicles rises, a relatively more significant additional net surplus will occur. It implies that when raising revenue, the tax rate significantly affects consumer surplus more than the tax type. However, as the proportion of electric vehicles increases, tax type also becomes important in determining a tax rate and changing the consumer surplus.

Chapter 3 discusses the second-best optimal taxes by the three tax types considering the expansion of EVs in the US: gasoline tax, VMT tax, and combined tax of gas and VMT taxes. According to the model developed in this paper, the second-best optimal tax rates of flat VMT and flat VMT+gas taxes, converted in cents per gallon, are higher than the second-best optimal gas tax. However, both rates can improve social welfare more than the gas tax. The flat VMT+gas tax generates a significant welfare benefit as much as the VMT tax at the second-best optimal rates. In the early stage of introducing electric vehicles, among the best revenue-neutral taxes to maintain the current government revenue, only the flat VMT+gas tax provides positive welfare benefits. As long as the EV share does not exceed 40%, the flat VMT+gas tax is more favorable than the flat VMT tax. The EV VMT+gas tax is more advantageous regardless of the EV share than the VMT tax types capped with the current government revenue.

These three papers contribute to understanding of how the share of electric vehicles affects the surplus from the policy shift from a gasoline tax to a VMT tax. The cost of switching tax policies makes policymakers hesitant to adopt the new tax policy. However, the results of this dissertation provide evidence that adopting the new tax policy can benefit both private and public alike if sustained EV growth is to be expected.

Contents

CHAPTER 1

Distributional Effects of A Vehicle Miles Traveled Tax over the Different Vehicle Efficiency

1.1. Introduction

By the end of 2021, US electric vehicle sales have risen to 4.8%. It is remarkable growth considering that electric vehicle (EV) sales were around 1% at the end of 2017, only four years ago. According to one forecast, EVs on the road will account for around 7% in 2030[1]. One of the optimistic forecasts suggests that the EV share of new car sales will be 30% within decades[2]. Also, passenger cars improved from an average of 20.7 miles per gallon (MPG) in 1994 to 24.4 miles per gallon in 2018[3]. One institute argues that the equivalent tax per vehicle miles traveled (VMT) was reduced from 3.2 cents in 1994 to 2.1 cents in 2018[4]. Since electric vehicles do not pay any gasoline tax, and high-efficiency vehicles also pay fewer gasoline taxes, the growth of EV sales and fuel-efficient vehicles makes fundraising from the gasoline tax more challenging. Without political actions, the gasoline tax will yield more significant discrepancies between tax revenues and highway expenditures. A VMT tax could be one option to mitigate the problem and maintain funding for US highways by charging all drivers on the road based on miles traveled. Some states and the federal government have considered the tax policy shift from a gasoline to a VMT tax because of tax revenue. For instance, Oregon started "OReGo", where participants pay 1.8 cents for each mile and receive a pay-back of 36 cents per gallon fuel tax. Also, the Biden

[1] Adam Cooper and Kellen Schefter, "Electric Vehicle Sales Forecast and the Charging Infrastructure Required through 2030", Edison Electric Institute, Nov.2018, http://www.ehcar.net/library/rapport/rapport233.pdf.
[2] https://evadoption.com/ev-sales/ev-sales-forecasts/
[3] Light-duty vehicles short wheelbase, EIA, https://www.eia.gov/totalenergy/data/browser/?tbl=T01.08
[4] Ulrik Boesen, "Who Will Pay for the Roads?", Tax Foundation, Aug.2020, https://taxfoundation.org/state-infrastructure-spending/.

administration's infrastructure bill includes $125 million to fund a pilot program to test a national VMT tax.

This paper examines the impact of operating cost, defined as the private cost incurred for each mile driven in a vehicle, on vehicle choice and driving. The estimate results evaluate the short-term distributional impact of switching from a gasoline tax to a VMT tax to maintain government revenues. The policy shift from a gasoline tax to a VMT tax has heterogeneous operating cost effects, depending on vehicle and household characteristics. To assess the distributional impacts, it measures the gains and losses of tax translation by division: vehicle types, such as electric vehicles and non-electric vehicles, including internal combustion engines (ICEs) and conventional hybrids (Hybrids), fuel economy, income, urban or rural residence, having children or not, working or retired, states, and census division. Also, it estimates the rate of each tax needed to sustain the government revenue as EV penetration grows and the impact of that tax on consumer surplus.

A two-period model is developed with reference to Gillingham (2011) and Bento et al. (2009). The two-period model consists of a utility function for purchasing a vehicle in the first period and a utility function for driving in the second period. The expected driving influences vehicle choice, while the miles driven are chosen conditional on the vehicle. The model is estimated consistently by simultaneously estimating both utility functions in the two periods. The parameters, assumed as random coefficients, allow for heterogeneity of unobserved household preferences for vehicle selection and utilization decisions. It improves the accuracy of examining distributional effects by household and vehicle attributes. Also, the model has an explicit operating cost structure to illustrate the operating cost effects by tax types. This paper evaluates the operating cost as the per-mile cost of EVs and non-EVs in the same unit to conduct a counterfactual analysis of policy shifts.

The three factors influencing changes in consumer surplus are fuel economy, operating cost, and VMT elasticity of operating costs. In the counterfactual analysis, the VMT tax generates a slightly positive consumer surplus of $2 per vehicle per year, compared to the gasoline tax when collecting the same government revenue. The gains from ICEs with higher average mileage offset losses from EVs with lower average mileage. The positive consumer surplus is also because households with a low VMT elasticity tend to own cars with lower fuel economy and drive more than households with a high VMT elasticity.

The estimate results also examine the heterogeneous impact of VMT taxes on consumer surplus by vehicle type, fuel economy, region, and income. Less efficient vehicles benefit from the policy shift from gasoline to VMT tax, while more efficient vehicles lose. EVs are all worse off by the newly charged tax. Even with converting to the same federal VMT tax, the consumers in some states gain, while the others lose. The result over income implies that the VMT tax is more regressive than the gasoline tax. In addition, the sensitivity analysis results show that the distributional effects over the vehicle and household characteristics from the tax policy change are consistent regardless of the increase in government revenue.

Ultimately, the sensitivity analysis supports that if EV penetration continues to grow, a sooner policy transition to a VMT tax is more efficient as it can benefit from reducing the discrepancy between revenue and expenditure without changing the tax rate. Introducing a VMT tax allows the government to maintain the tax rate independent of the EV proportion. At the same time, the deficit can be covered by taxing electric vehicles. When the EV share reaches 5%, there is twice as much additional net benefit from the introduction of the VMT tax than from switching to the VMT tax without accounting for changes in the EV share. The sensitivity analysis in this paper considers the case of increasing EV market share up to 10%, and the net benefit gradually increases as EVs grow. It suggests expectations that net benefits from the tax policy transition will continue to grow as EVs continue to rise. It implies that the opportunity cost to keep the gas tax policy is increased as the EVs grow.

This result has implications for governments to consider adopting a VMT tax at a time when EV share is expected to increase. Indeed, it focuses on consumer surplus changes from introducing a VMT tax replaced with a gas tax. Nonetheless, the results show that the VMT tax is more efficient than a gas tax. The primary analysis sustains the government revenues the same. Also, it is still being determined whether the environmental benefit of driving EVs has stringent. As long as the change in total mileage after changing the tax is negligible, the VMT tax is more efficient.

This paper is not the first to evaluate a VMT tax replaced with a gasoline tax. Langer et al. (2017) and McMullen et al. (2010) estimate the fuel cost effects on driving mileage to evaluate VMT tax. Weatherford (2012) and Metcalf et al. (2022) discuss the distributional implications of a VMT tax by income. Meanwhile, this paper evaluates private welfare changes in the short term depending on fuel types, fuel efficiency, and household characteristics, considering the penetration of EVs growth. Although the electric vehicle accounts for a small market share, the rising EV share is essential to analyzing the welfare change of VMT tax. The growth of electric vehicles directly increases the proportion of fuel-efficient vehicles. Langer et al. (2017) suggests that a VMT tax improves welfare more than a gasoline tax as the share of high MPG vehicles increases. Also, introducing a VMT tax can newly charge a tax on EV driving. This paper bridges the gap between predictions considering EV share and empirical results evaluating VMT taxes.

The rest of the paper is structured as follows. Section 2 describes the relevant literature and briefly provides the background of VMT tax and alternative vehicle fuel types. Section 3 presents the theoretical framework and the econometric model. Section 4 provides the data information and main assumptions. The following two sections describe the estimate results and counterfactual analysis. The last section concludes.

1.2. Background

This section presents the literature review. In addition, it provides the background focusing on the recent discussions of a VMT tax and the definition of the vehicle fuel types used in the empirical analysis.

1.2.1. Literature Reviews. Much of the literature has produced empirical studies about fuel prices in the US, primarily to evaluate various policies to address externalities in the transport sectors, such as gasoline taxes and Corporate Average Fuel Economy (CAFE) standards (Goldberg (1998) ;Kleit (2004); Bento et al. (2009); Hymel and Small (2015); Liu (2015)). Most papers estimate the gasoline price elasticity of gasoline consumption or miles driven and the per-mile cost elasticity of vehicle miles traveled.

A significant portion of the literature has studied a gasoline tax. One of the notable studies on gasoline tax impacts is Bento et al. (2009). It jointly estimates vehicle selection and utilization from a static model that captures the impacts of US gasoline tax increases. They suggest that the gas price elasticity of gas consumption and the operating cost elasticity of VMT for the 1996-2008 period in the US are -0.35 and -0.74, respectively. Li et al. (2014) separately estimate the effects of gasoline price and gasoline tax on gasoline consumption and VMT using log-linear regression and first-differenced estimating equations. They provide that the gasoline tax elasticities of gas consumption and VMT are around -0.172$\sim$-0.365 and -0.066$\sim$-0.496 respectively, in the US for 1996-2008. They point out that the effect of the gasoline tax is greater than the tax-exclusive-gas price effect. Gillingham (2011) uses a joint choice model to estimate vehicle choice and utilization from a dynamic model. The author uses a rich dataset of all vehicle registrations from 2001-2009 in California. He reports that the gas price elasticity of fuel economy is 0.09, and the elasticity of driving is -0.15. A common concern in the literature is the endogeneity of gasoline prices or vehicle efficiencies from unobserved consumer preferences or vehicle attributes. Li et al. (2014) uses the instrumental variables to mitigate the problem, while Bento et al. (2009) and Gillingham (2011) use structural analysis to address the problem.

A substantial body of literature relative to CAFE has studied the rebound effect, which means that higher fuel economy could increase VMT by reducing per-mile driving costs. Small and Van Dender (2007) present the per-mile operating cost elasticities of VMT, defined as a rebound effect in the paper, are -0.045 for the short-run and -0.222 for the long-run. The results are estimated with 2SLS and 3SLS for the US over 1966-2001. They report that the effect diminishes substantially as real income rises. Linn (2016) defines the rebound effect as the fuel economy elasticity of VMT considering the household's other vehicle fuel economy, estimated at around 0.22∼0.44. He criticizes the three main assumptions that the literature makes to estimate the rebound effect. The first assumption is that fuel economy is uncorrelated with household characteristics or vehicle attributes. Also, each vehicle is treated as an independent observation for multi-vehicle households. The last one is that the gasoline price effect is inversely proportional to the fuel economy effect. Linn (2016) relieves these assumptions by using IV estimates, controlling for the fuel economy of the household's other vehicle, and allowing for separating coefficients on the gasoline price and fuel economy.

There is comparatively little empirical work on VMT tax. Langer et al. (2017) initiates the national assessment of a VMT and gasoline tax to raise government revenue. The log-linear estimating equation estimates the per-mile driving cost elasticity of VMT, which is -0.150∼-0.191. The endogeneity problem is controlled by including household fixed effects and macroeconomic and weather variables. They find that the VMT tax is more efficient than the gasoline tax. More recent studies about VMT tax is Davis and Sallee (2020), which studies VMT tax and electric vehicles. They concentrate on whether the EV driver should pay mileage tax or not and report that 1% EV shares of the total registered vehicles have reduced gas tax revenues by $250 million annually in the US. Weatherford (2012) and Metcalf et al. (2022) present the distributional implications of a VMT tax. Both papers focus on the distributional effect on income. The former suggests that the tax rate has a greater effect on welfare than the type of tax policy; a gas tax or VMT tax. The latter finds that switching to a VMT tax slightly increases the tax share of income as income increases. On the other hand, this paper analyzes the consumer surplus change from adopting the VMT tax primarily over fuel economy and explicitly considers EVs' penetration.

1.2.2. Main Issues about a VMT Tax. Revenue generation, externalities, and public acceptance generally matter when adopting a new policy. A VMT tax is less motivating to buy a more fuel-efficient vehicle than a gas tax. Also, it often raises fairness issues because it is slightly more regressive than the regressive gas tax (McMullen et al. (2010)). Another concern about introducing a VMT tax is the technical issue of collecting mileage data related to personal data. These issues make public acceptance difficult. However, externalities and public acceptance are out of scope as this report focuses on the tax impact on consumer surplus. This paper, therefore, discusses the revenue generation and the private welfare effects of the VMT tax.

Since 1993, the federal gasoline tax has remained unchanged at 18.4 cents[5]. The gasoline taxes are almost steadfast and not indexed to inflation. State gas taxes are also rarely raised. In addition, the vehicle's fuel economy has gradually improved. The fuel types, such as hybrid or electric vehicles, also reduce tax revenues. The federal gasoline tax is spent on maintaining or developing public transportation or infrastructure through the US Highway Trust Fund (HTF). However, according to a May 2022 report by the Congressional Budget Office, HTF's highway cumulative balance deficit is expected to grow continuously from $4.7 billion in 2027 to $17.1 billion in 2030, even after the $90 billion transfer from the general fund of Treasury in 2022. One notable option to resolve this problem is a VMT tax. The National Surface Transportation Infrastructure Financing Commission (NSTIF) suggests that a VMT tax can be an option to raise fund revenue[6]. NSTIF[7] reports that charging 1 cent per mile on every vehicle and every road could yield $30 billion. Only 0.033 cents per mile tax can raise $ 1 billion a year. Many states also consider the adoption of a VMT tax. Some states, including Oregon, Minnesota, and Washington, implement pilot programs to test VMT tax (Duncan et al. (2017)). Recently, the US Senate passed Biden's infrastructure bill, which includes $125 million to fund pilot programs to test a national VMT tax.

1.2.3. Definition of Vehicle Fueltype. There are various alternative fuel vehicles available today. The most common alternative fuel vehicles are conventional hybrid electric vehicles (HEV). The gasoline engine of a conventional hybrid charges the battery during driving, but the battery pack cannot be recharged by plugging it into a charger. Conventional hybrids have slightly higher

[5]The gas tax dropped a tenth of a cent for Jan.1996-Sep.1997, but went back to 18.4 cents.
[6]https://financecommission.dot.gov/Documents/NSTIF_Commission_Final_Report_Mar09FNL.pdf
[7]Paying Our Way, 2009, NSTIF

fuel efficiency and price than their ICE counterparts. For example, Ford Escape Hybrid's MPG is up to 44 city/37 highway, while Ford Escape ICE's MPG is up to 28 city/34 highway. Also, the manufacturer's suggested retail price (MSRP) for Ford Escape in 2021 is $27,605 for hybrid and $26,610 for ICE. In this paper, hybrid denotes the conventional hybrid.

Electric vehicles consist of Plug-in Hybrid Vehicles (PHEVs) and Battery Electric Vehicles (BEVs). Although PHEVs can use a combination of the gas engine and electric motor, PHEVs use batteries to drive on pure electric power without burning other fuel, unlike HEVs. BEVs drive only on battery power dispensing with the gas engine. PHEVs and BEVs require a large battery pack to provide a specific range of miles to travel before they need to be charged. It causes a higher price for EVs than their ICE counterparts. For example, the 2021 Ford Escape PHEV's MSRP is $33,075 (MPGe 100 combined city/highway), which is around $6,000 and $5,000 higher than the same ICE and conventional hybrid model, respectively. Also, Nissan LEAF, one of the popular BEVs, is $31,670 based on MSRP (MPGe 123 City/99 highway), while Nissan Versa, which has similar dimensions to LEAF, is $14,980 (32 city/40 highway). In this paper, EVs denote PHEVs and BEVs.

Apart from hybrids and electric vehicles, there are other alternative fuel vehicles for light-duty: FFV (Flexible Fuel Vehicle, e.g., E85), CNG (Compressed Natural Gas), propane, and Hydrogen Fuel Cell. According to the Alternative Fuels Data Center (AFDC) of the US Department of Energy, FFVs, HEVs, and EVs account for 80.6%, 15.5%, and 3.7% in 2018, respectively. FFVs generally operate primarily on gasoline. The other alternative fuel vehicle share is tiny, around 0.2%. Therefore, this paper classifies fuel types into ICE, conventional hybrid, and EV.

1.3. Model

1.3.1. Theory of Consumer Surplus. This paper presents a conceptual model of consumer surplus that evaluates the impact of policy changes to support empirical analysis. Consider two markets indexed by g and e, each using gasoline and electricity to drive, respectively. Assume that the consumer surplus, $v(p)$, is a function of the price, p, and is convex. Price refers to the operating cost per mile to drive. For a household that owns an ICE subject to a gas tax, the operating cost is p_g, the sum of the gas price excluding tax (c_g) and the gasoline tax (t_1) divided by the MPG ($p_g^1 = \frac{c_g+t_1}{MPG}$). With a VMT tax ($t_2$) applied, the operating cost of an ICE holder is the sum of the gas price divided by MPG and tax ($p_g^2 = \frac{c_g}{MPG} + t_2$). If a household drives an electric vehicle, operating costs (p_e) are electricity prices per mile without a gasoline tax ($p_e^1 = c_e$). When VMT tax is applied, it is the sum of the electricity price and tax($p_e^2 = c_e + t_2$). According to Roy's identity, the marginal utility of price is $v'(p) = -m(p)$, where $m(p)$ is a function of demand for driving.

The change in consumer surplus when a tax shift from a gas tax to a VMT tax is $\triangle v_g \equiv v(p_g^2) - v(p_g^1)$ for ICE holder, and $\triangle v_e \equiv v(p_e^2) - v(p_e^1)$ for EV holder.

The convex function of consumer surplus implies,

$$-(p_g^2 - p_g^1)m(p_g^1) < \triangle v_g < -(p_g^2 - p_g^1)m(p_g^2) \tag{1.1}$$

$$-(p_e^2 - p_e^1)m(p_e^1) < \triangle v_e < -(p_e^2 - p_e^1)m(p_e^2) \tag{1.2}$$

Proposition. If the miles driven under the VMT tax are equal to or greater than the miles driven under the gas tax, the revenue-neutral VMT tax improves the total consumer surplus.

Proof. Consider the total number of ICE holders, D_g, and EV holders, D_e. Then, the total consumer surplus change is $\triangle V \equiv \sum_{i=1}^{D_g} \triangle v_{i,g} + \sum_{i=1}^{D_e} \triangle v_{i,e}$. From (1.1) and (1.2),

$$\begin{aligned}&\sum_{i=1}^{D_g} m_i(p_g^2)\frac{t_1}{MPG_i} - (\sum_{i=1}^{D_e} m_i(p_e^2) + \sum_{i=1}^{D_g} m_i(p_g^2))t_2 \\ &> \triangle V > \sum_{i=1}^{D_g} m_i(p_g^1)\frac{t_1}{MPG_i} - (\sum_{i=1}^{D_e} m_i(p_e^1) + \sum_{i=1}^{D_g} m_i(p_g^1))t_2\end{aligned} \tag{1.3}$$

If the government imposes a VMT tax to collect the same government revenue as the gas tax, the VMT tax satisfies the equation (1.4).

$$(\sum_{i=1}^{D_g} m_i(p_g^2) + \sum_{i=1}^{D_e} m_i(p_e^2))t_2 = \sum_{i=1}^{D_g} \frac{m_i(p_g^1)}{MPG_i} t_1 \tag{1.4}$$

With using (1.4), (1.3) is rewritten as

$$\begin{aligned} t_2(\sum_{i=1}^{D_g} m_i(p_g^2) + \sum_{i=1}^{D_e} m_i(p_e^2))(\frac{\sum_{i=1}^{D_g}(m_i(p_g^2)/MPG_i)}{\sum_{i=1}^{D_g}(m_i(p_g^1)/MPG_i)} - 1) \\ > \triangle V > t_2((\sum_{i=1}^{D_g} m_i(p_g^2) + \sum_{i=1}^{D_e} m_i(p_e^2)) - (\sum_{i=1}^{D_e} m_i(p_e^1) + \sum_{i=1}^{D_g} m_i(p_g^1))) \end{aligned} \tag{1.5}$$

The lower bound is the product of the VMT tax and the change in total driving consumption due to the tax shift. The VMT tax generates a positive consumer surplus as long as a decrease in driving by EV holders is offset by an increase in driving by ICE holders. This stylized model proposes results consistent with the empirical model approach in the next section.

1.3.2. The Econometric Model. A two-period model is developed to estimate the impact of operating costs on vehicle selection and miles driven. The structure of the utility function is modified from the model of Gillingham (2011). The model assumes two utility functions of vehicle selection in the first period and subsequent utilization in the second period. In the first period, households optimally choose a vehicle based on vehicle attributes, income, vehicle price, the expected resale price of the vehicle, and the expected utility for driving the vehicle in the second period. In the second period, households select miles driven based on vehicle attributes, household characteristics, and operating costs conditional on the vehicle selected in the first period. The discrete-continuous model estimates vehicle choice and utilization by assuming that households consistently consider both decisions over the two periods.

Utility function for utilization in the second period

The utility in the second period is assumed as a concave function. Each household i optimally chooses miles driven M_{ij} conditional on the vehicle j based on each household characteristics and vehicle attributes α_{ij}, the operating cost c_{ij}, and the curvature of the function λ_i. α_{ij} is a vector of the alternative vehicle and household characteristics z^{α}_{ij}, and its parameters $\tilde{\alpha}_i$. The household characteristics include the number of workers in the household, working or retired status, having children or not, homeowner status, average adult age, race (white or not), education levels (above college or not), six levels of population size of the Metropolitan Statistical Area (MSA)[8], and six income groups. The vehicle attributes included in z^{α}_{ij} are horsepower, the vehicle types (car, van, SUV, and pickup truck), and fuel types (ICE, Hybrid, and EV). Additionally, included in z^{α}_{ij} are the average operating cost and VMT of the other vehicles in the household's garage. In this model, the household chooses one vehicle, not a portfolio. According to the 2017 NHTS, 33.6% of households having vehicles own a single vehicle, and another 40.5% of households own two vehicles. The rest own three or more vehicles. However, considering the 362 vehicle compositions, the bundle choice would create a large computational burden. Even considering only two car bundles, 65,703 choice sets are required. Including the operating cost and VMT of the substitutional vehicles in the household's garage can reduce the problem of the assumption that the household chooses a single vehicle on each occasion. The household purchases a vehicle among J vehicles considering the other vehicles' operating costs and VMT in their garage if they have two or more vehicles. The variable c_{ij} is the operating cost per mile defined as equation (1.6). g_i is the price of gasoline, excluding a tax, if the vehicle j is not an EV. Otherwise, it is the price of electricity converted to the gas equivalent prices, i.e., cents per gallon. t_1 is a gasoline tax, t_2 is a VMT tax, and MPG_j is vehicle j's fuel efficiency, miles per gallon. If a gas tax, t_1, is imposed, the tax raises costs depending on the fuel efficiency. The VMT tax, t_2, raises the operating cost without distortion.

[8]2017 NHTS provides Population size category of MSA from the 2010 - 2014 five year American Community Survey API. It classifies MSAs into six bins according to population: MSA of less than 250k, 250k - 500k, 500k-1,000k, 1,000k-3,000k, over 3 million, and not in MSA or CMSA(consolidated metropolitan statistical areas).

Since EVs do not use gasoline, EVs are only imposed with t_2, not t_1. λ_i allows each household to have a different utility function by diminishing the marginal utility of driving differently. The marginal utility decreases slower as λ_i is larger. All parameters in $\tilde{\alpha}_i$ and λ_i vary randomly across households.

$$
\begin{aligned}
U_{2,ij}(z^{\alpha}_{ij}, c_{ij}) &= \frac{1}{\alpha_{ij}}(M_{ij} - \frac{1}{2\lambda_i}M^2_{ij}) - c_{ij}M_{ij} \\
\alpha_{ij} &= -\tilde{\alpha}_i z^{\alpha}_{ij} \\
c_{ij} &= \begin{cases} (t_1 + g_i)(1/MPG_j) & \text{if the gasoline tax imposed} \\ t_2 + g_i(1/MPGj) & \text{if the VMT tax imposed} \end{cases}
\end{aligned}
\tag{1.6}
$$

The household maximizes utility by selecting the driving, M_{ij}, conditional on the vehicle j, assuming an interior solution. The specific functional form of the optimal choice, $\tilde{M}_{ij}$, is in (1.7). Since the household chooses the VMT conditional on the vehicle j, the optimized choice is repeated at t times for each household, where t is the number of vehicles the households have. Besides the optimal choice, households may be subject to shocks that can affect actual mileage at occasion t. For example, a household may move or change jobs. The shock is known when the consumer drives but not in the first period. Also, econometricians do not know. I assume that the shock denoted by η_{ijt} is normally distributed. Hence, the actual miles driven of household i using vehicle j at occasion t is M^*_{ijt}.

$$
\begin{aligned}
\tilde{M}_{ij} &= \underset{M_{ij}>0}{arg\,max}\, U_{2,ij}(z^{\alpha}_{ij}, c_{ij}) = \lambda_i - \alpha_{ij}\lambda_i c_{ij} \\
M^*_{ijt} &= \tilde{M}_{ijt} + \eta_{ijt} \qquad \eta_{ijt} \sim N(0, \sigma^2_i)
\end{aligned}
\tag{1.7}
$$

The optimal choice of driving depends on household and vehicle attributes and the operating cost. If the observed household characteristics are identical and have the same vehicle, the utility function would force them to have identical driving patterns. Adding all the random parameters and driving shocks reduces the problem.

Utility function for vehicle choice in the first period

Households are assumed to know their utility functions. The utility in the first period depends on the expected utility of the household in the second period at t, $E[U_{2,ijt}]$, the household and vehicle characteristics θ_{ij}, the household income y_i, the vehicle price p_{ij}, the interest rate r, and the expected resale price of the vehicle p_{ij}^R. This model assumes a risk-neutral utility function. In the first period, households take the expectation of the utility for driving and the resale price of vehicle j. Future gasoline prices and driving shocks for the utility in the second period are unknown in the first period. Households expect the future gasoline price based on the current price. The shock is unknown, so the mean is zero. The derivative for the expected utility in the second period is provided in the Appendix (1.A.1). θ_{ij} is a vector of the household and vehicle characteristics z_{ij}^{θ} and its parameters $\tilde{\theta_{ij}}$. It includes a constant to capture the fixed effect, 35 categories of MSA and public transportation[9], horsepower, vehicle types, fuel types, vehicle size (wheelbase, width, height), and brand (Chevrolet, Ford, Honda, etc.). y_i is income, and p_{ij} is vehicle j purchase price of household i. It is the value of the vehicle price minus subsidy. That is, P_j^v is the retail price of vehicle j, so identical for all households. sub_{ij} is a subsidy for vehicle j and varies by vehicle price, fuel type, household location, and income. Hence, p_{ij} varies by household and vehicle, as subsidies vary by household based on state, income, vehicle price, and fuel type. r is the real interest rate. The

[9]The 2017 NHTS provides 35 household classes grouping by a combination of census division, MSA status, and presence of a subway system when population greater than 1 million. In the data set used in this analysis, the valid bins are 33 categories.

households consider the opportunity cost of the vehicle j's price a year. One could think of it as the rental price of the vehicle j, or the annual car loan repayment amount. The expected resale price p^R_{ij} varies over households and vehicles according to the vehicle j's depreciation rate d_j, the vehicle price, and the optimal miles driven of household i with the vehicle j. Since the households would not know about the resale price in the future, they expect it based on their vehicle and driving miles chosen. μ_{ij} implies the adjustment factors for the resale price; the higher the mileage, the lower the expected resale price. Since households could have more than two vehicles in their garage, they have the decision to purchase a car repeatedly on every t occasion. ϵ_{ijt} is distributed i.i.d. Type I extreme value for a discrete choice model. The remaining letters are parameters, which are all random variables.

$$
\begin{aligned}
U_{1,ijt}(E[U_{2,ijt}], z^{\theta}_{ij}, y_i, p_{ij}, r, d_i, M^*_{ijt}) &= \delta_{1,i}E[U_{2,ijt}] + \theta_{ij} + y_i - rp_{ij} + \delta_{2,i}p^R_{ij} + \epsilon_{ijt} \\
\theta_{ij} &= \tilde{\theta}_i z^{\theta}_{ij} \\
E[U_{2,ij}] &= \lambda_i\left(\frac{1}{2\alpha_{ij}} - E[c_{ij}] - \frac{\alpha_{ij}}{2}(E[c_{ij}]^2 + var[c_{ij}])\right) \\
p_{ij} &= (P^v_j - sub_{ij}) \\
p^R_{ij} &= (1 - d_j)P^v_j - \mu_i E[M^*_{ijt}]
\end{aligned}
\tag{1.8}
$$

The main differences between this model and Gillingham (2011) are that all parameters are random variables. It can incorporate random taste variations of unobserved household preferences. Also, the model includes the average operating costs and VMT of other vehicles in the household's garage, which would have been considered replacements when selecting the vehicle and miles driven. Lastly, the operating cost is explicitly derived according to fuel types and taxes. This model's operating cost can give insight into the VMT tax effects across different fuel types. It can provide the simulation results of a tax policy shift and different tax rates.

The Stochastic Structure of the Two-period Utility Functions

A sequential procedure like in Dubin and McFadden (1984), Goldberg (1998), and West (2004) estimates two different results of the same parameter set. Feng et al. (2013) argues that it is inconsistent with the hypotheses of the sequential set of the utility function and the demand function derived from it. More recent literature (Feng et al. (2013), Spiller (2012), Jacobsen (2013), Bento et al. (2009), Gillingham (2011)) estimate the parameters simultaneously. This paper also follows the method. Two utility functions need to be maximized in this analysis. The utility has its parameter set separately, but the household considers a different time frame to make each decision. In the first period, households consider expected utility in the second period. In the second period, households choose the optimal miles driven conditional on the vehicle purchased in the first period. Therefore, this two-period model requires simultaneously estimating the utility functions for different periods to obtain consistent estimates.

From the first period in this model, ϵ_{ijt} is distributed i.i.d. Type I extreme value. Hence, the probability of consumer i to purchase vehicle j among J vehicles at occasion t are as follows:

$$Pr_{it}(j) = \frac{exp(U_{1,ijt})}{\Sigma_{k=1}^{J} exp(U_{1,ikt})} \tag{1.9}$$

Another stochastic term is from the second period. η_{ijt} is assumed as i.i.d. normal distribution with zero mean and an unknown variance σ_i. Conditional on vehicle j, the likelihood function of household i at occasion t is:

$$l(M^*_{ijt}|j\ chosen) = \frac{1}{\sqrt{2\pi\sigma_i^2}} exp(-\frac{1}{2}(\frac{M_{ijt} - M^*_{ijt}}{\sigma_i})^2) \tag{1.10}$$

The full likelihood function of household i to estimate both demands simultaneously is then,

$$L_i = \Pi_{t=1}^{T_i}[\Pi_{j=1}^{J} Pr_{it}(j)^{1_{ijt}} \Pi_{j=1}^{J} l(M_{ijt}^{*}|j\, chosen)^{1_{ijt}}] \tag{1.11}$$

where 1_{ijt} is an indicator function equal to one if household i purchases vehicle j at occasion t, otherwise zero. The full likelihood allows estimating the set of parameters, $\Theta = (\tilde{\alpha_i}, \lambda_i, \tilde{\theta}_i, \delta_{1,i}, \delta_{2,i}, \mu_i, \sigma_i)$, in (1.6) $\sim$ (2.5).

1.4. Data and Assumptions

1.4.1. Data Description. The primary data set is the 2017 National Household Travel Survey (NHTS) by the US Department of Transportation. The NHTS data reports 256,115 vehicles with vintages from 1977 to 2017. To focus on passenger cars and control measurement errors, I delete some specific types of vehicles (e.g., recreational vehicles, motorcycles/motorbikes), missing data (i.e., no answers), and measurement error[10]. Then, 84,531 vehicles left. This paper analyzes new car purchases from 2016 to 2017, when EVs have the highest share in the datasets, focusing on the tax effect of various vehicle fuel types. It reflects the recent larger share of electric vehicles. Electric vehicles account for 0.4% of all registered vehicles but rise to 1.3% and 2.4% in 2016 and 2017 vehicle vintages, respectively. It also alleviates the problem of no vehicle purchase time data for estimating the purchase price by household in the 2017 NHTS. Finally, data is composed of 12,555 vehicles from 11,850 households for analysis.

This data has rich information on vehicle properties and household characteristics. Vehicle attributes include the brand (e.g., Ford, Honda), model, vintage, vehicle type (car, van, SUV, pickup truck), horsepower, and MPG. It also provides vehicle fuel types that can be classified into ICE, conventional hybrid, and EV (BEV, PHEV), which are the main categories of this paper. It has information about households, such as income range in dollars, vehicle miles traveled, residence

[10]2017 NHTS has two types of variables in terms of fuel type. One is FUELTYPE (gas, diesel, hybrid, electric or alternative fuels). The other is HFUEL, which is divided into plug-in hybrids, electric and conventional hybrids. If the information does not match, the data is deleted. For example, the data of response to plug-in hybrid for HFUEL and response to gas for FUELTYPE is dropped.

(state, city, or rural), family composition (with or without children), number of vehicles, number of workers, and homeowner status. Household income is provided in one of 11 income groups, not dollar amounts. I classify them into six groups and assign the median of the income group to each household's income.

Gasoline prices are obtained from Energy Information Administration (EIA) and US Bureau of Labor Statistics (BLS) data. EIA's gasoline prices are state-level, while BLS provides specific urban areas. To obtain a more diverse range of gasoline prices, I merge specific regional gasoline prices in the BLS with the NHTS data by the Core Based Statistical Area (CBSA). Next, the rest of the data is presented at the state level by merging the EIA's gasoline prices into the NHTS. The electricity rates by state are taken from the EIA.

The US Market Database of Dataone provides MSRP and MPG/MPGe[11] of vehicle models. The 2017 NHTS classifies similar models into one class (e.g., Caravan and Grand Caravan are in the same class) and does not divide models according to their driveline (AWD, FWD, or RWD). So, I take the average MSRP of Dataone according to the NHTS model class and merge it into the NHTS data. Conventional hybrid and plug-in hybrids have both MPG and MPGe as their attributes. This paper supposes that people mainly use gas to drive conventional hybrids and electricity to drive PHEVs. So, it uses MPG for conventional hybrids from NHTS and MPGe for PHEVs from Dataone. However, even when using MPG for PHEV, the difference in results is negligible.

AFDC of the Department of Energy provides data about the state's EV subsidies or grants. Table 1.B.1 in Appendix shows the list of subsidies in effect during 2016-2017 to estimate the actual purchase price of a household's vehicle. Considering the subsidy, the price of the same vehicle models varies from household to household, depending on the household's location, income, and the alternative vehicle price. Depreciation rates vary by car model, make, and mileage. The source

[11]MPGe represents the EV's miles per gallon of gasoline-equivalent. It is introduced by the Environmental Protection Agency (EPA). It can be used to compare the energy consumed by an alternative fuel vehicle to an ICE.

of car depreciation rates is CarEdge[12]. All dollar value variables are adjusted to 2021 dollars using the Bureau of Labor Statistics (BLS) consumer price index.

Table 1.1 shows the representativeness of the population by comparing all samples from the 2017 NHTS to the data set used in this paper. As this paper includes only newly purchased vehicles, the average MPG and MSRP are higher than the entire data set of the 2017 NHTS[13]. However, other attributes are similar[14]. Table 1.2 reports vehicle and household attributes by fuel type. As expected, operating costs per mile are the lowest in the order of EVs, hybrids, and ICEs. In contrast, MPG/MPGe is the highest in the same order. VMT does not just increase by cost per mile. ICE owners drive the most, and EV owners drive the least. It means that utilization choices depend not only on operating costs but also on other characteristics of the households or vehicles. The relationship between the average MSRP and income implies that EVs are primarily affordable for high-income groups. It also reports the percentage of vehicle fuel types (ICE, EV, and Hybrid) by urban or rural area, having children or not, working or retired. It shows the preference of the fuel type by household characteristics. For example, households with children, living in cities, and working prefer EVs over other groups.

1.4.2. Data Assumptions. Several assumptions are made about the choice sets and household expectations to apply the data set to the model. The 2017 NHTS was conducted from April 2016 to March 2017. Some vehicles manufactured in 2016 may not be new purchases. However, the residual value after depreciation of one year is around 90%. Then the value of a used car less than a year old is close to the price of the new car. Therefore, all car models produced in 2016-2017 are assumed to be 2016 new car purchases. Households consider vehicles sold in 2016-2017 to be a choice set. Then, in this discrete selection of the first period, the set of alternatives is the 362-year-model choices.

[12]CarEdge.com is a private company based on a website that provides vehicle information that consumers may consider for purchasing a vehicle.
[13]MPG from the sample used for this analysis is merged with the dataset of Dataone using MPGe for PHEV. It also increases the average MPG of the sample.
[14]Tables 1.B.2 and 1.B.3 in Appendix 1.B.1 present each region's average gasoline price, MPG, and VMT. The samples used in this analysis tend to be similar to the statistics of the whole sample.

Table 1.1. **Summary Statistics: NHTS and Sample in the Analysis**

		NHTS(2017)	Sample			
	OBS	84,531	12,555			
Variables		Mean	Mean	Std Dev.	Min	Max
Gas price	$/gallon ($2021)	2.5	2.5	0.3	2.1	3.4
average MPG[a]	Miles/gallon	24.4	26.0	10.6	13.4	133.0
vehicle MSRP	$ ($2021)	33,396	36,029	12,692	16,648	176,794
Horsepower	-	229	233	73	74	596
Average VMT	miles	12,105	12,987	8,530	108	58,908
Average income	$ ($2021)	118,052	126,203	90,064	5,527	331,638
Number of workers	-	1.3	1.3	0.9	0.0	7.0
average age among adults	-	53.2	53.6	15.0	19.0	92.0
Child	-	0.22	0.21	0.41	0.00	1.00
Home owner	-	0.85	0.85	0.36	0.00	1.00
White	-	0.86	0.86	0.35	0.00	1.00
College	-	0.92	0.92	0.27	0.00	1.00
Fuel Types						
EV	%	0.8	1.4	-	-	-
ICE	%	95.5	95.7	-	-	-
Hybid	%	3.7	2.9	-	-	-
Vehicle Types						
car	%	52.4	45.4	-	-	-
van	%	4.6	3.9	-	-	-
SUV	%	31.4	38.6	-	-	-
Pick-up	%	11.6	12.1	-	-	-
MSA size						
MSA Less than 250k	%	15.9	15.1	-	-	-
MSA of 250k - 500k	%	9.8	10.0	-	-	-
MSA of 500k - 1,000k	%	14.3	14.0	-	-	-
MSA of 1,000k - 3,000k	%	15.8	15.8	-	-	-
MSA of 3 million or more	%	30.5	32.8	-	-	-
Not in MSA	%	13.8	12.4	-	-	-

Notes: Sources are described in the text. [a] The average MPG of the sample used in this analysis is the data after merging with Dataone. The mean is higher than before merging. The mean of the same samples from 2017 NHTS before merging is 25.4.

The second assumption for estimating the model is household beliefs in the first period about the price of gasoline or electricity for the second period. A common assumption for gasoline price expectations is that the projected future price is equal to the current gasoline price (Anderson et al. (2013), Gillingham (2011)). According to the EIA, four factors determine the price of gasoline: crude oil costs, refining costs and profits, marketing costs and profits, and taxes. The gasoline tax persists, and crude oil and gasoline prices are stable during the 2016-2017 analysis period. So,

Table 1.2. **Summary Statistics: Household and Vehicle Characteristics by Fuel Types**

	EV	ICE	Hybrid	Total
Vehicle Miles Travel (Miles)	11,180	13,022	12,706	12,987
operating cost(cent,$2021)	0.6	10.6	6.5	10.3
Horsepower	218	235	166	233
average MPG^a	98.8	24.4	42.2	26.0
MSRP ($2021)	53,356	35,851	33,458	36,029
Income	199,108	124,432	149,329	126,203
Urban (%)	1.7	95.3	3.1	100.0
Rural (%)	0.5	97.2	2.2	100.0
Child (%)	1.8	95.6	2.5	100.0
No Child (%)	1.3	95.7	3.0	100.0
Work (%)	1.6	95.7	2.7	100.0
Retired (%)	0.9	95.7	3.4	100.0

Notes: Sources are described in the text. ^{a} The average MPG is the data after merging 2017 NHTS with Dataone.

it is assumed that the household believes the gasoline price as of 2016 is the expected gas price for the following year. It complies with the general assumptions of the literature, and regional variations can be obtained. For robustness, the same analysis is conducted using EIA forecasts for 2016 annual gasoline prices in January 2016.

The final assumption is regarding the depreciation rate, which is one of the components of the expected resale price of the vehicle in the first period. I take the five-year depreciation rate of each vehicle model driving 12,000 miles provided by CarEdge. The depreciation rates by model and manufacturer are merged with the 2017 NHTS data. I apply five-year depreciation rates but, for robustness, conduct the same analysis with 10-year depreciation rates.

Limited data requires additional assumptions. It is assumed that the vehicle price equals the MSRP and that all consumers are reasonable enough to be granted eligible EV subsidies. Therefore, the vehicle purchase price used in this paper is the MSRP after deducting alternative fuel vehicle subsidies by household and vehicle. Also, the average 10-year T-Bill from 2016-2017 is used as the real interest rate to estimate the opportunity cost of the vehicle price per year.

1.5. Estimation

1.5.1. Estimation Strategy. This paper takes the two-period structural model approach described in section 1.3.2. The random coefficient is one of the main differences from Gillingham (2011). All parameters, $\Theta = (\tilde{\alpha}_i, \lambda_i, \tilde{\theta}_i, \delta_{1,i}, \delta_{2,i}, \mu_i, \sigma_i)$, are assumed to follow a multivariate normal distribution. Random coefficients incorporate unobserved consumer preferences and allow for heterogeneity in household vehicle purchase and driving choices, even in the same functional form of utility functions. It reduces concerns that two households with the same characteristics and vehicles will be forced to have the same choice.

This paper employs Bayesian statistics to estimate the parameters. It uses the Gibbs sampler for Bayesian computation, which is one of the Markov Chain Monte Carlo (MCMC) simulation techniques (Bento et al. (2009)[15]). Although the literature on EVs is growing, to my knowledge, it is the first time that vehicle and utilization choices are simultaneously estimated while considering EV shares. In the absence of a reasonable starting value considering the EV, the Gibbs sampler has the advantage that no starting value is required to estimate the parameters. Bayesian statistics require an initial belief in the prior probability distribution. However, the MCMC procedure iteratively simulates a random sample set of parameters from the Θ distribution over the previous set. Because it uses randomly chosen initial values, the Gibbs sampler generates simulations from the unconditional posterior and ignores a sufficiently long burn-in. Each 10th simulation after 30,000 burn-in is used in this analysis to estimate parameters.

Additionally, the 2017 NHTS does not include information on whether respondents bought a new or used car. So, this paper uses only datasets of cars manufactured in 2016 or 2017 surveyed in 2017 by assuming that it is a new car purchase. It excludes the outside option (no purchasing a vehicle) and only includes the households already deciding to buy a new vehicle. The model captures how households select vehicles among new vehicles and how much they drive with them. It then provides a way to analyze the impact of changing operating costs through gas or VMT taxes on

[15]This methodology is similar to Bento et al. (2009). The coding for this analysis is referred to and modified from Bento et al. (2009) at https://www.openicpsr.org/openicpsr/project/113302/version/V1/view

the vehicle and utilization choices. Since the data focuses on new vehicle purchases, some concerns may arise. First, it cannot distinguish between buying a new car and using public transportation. This paper aims to find tax shift impacts on choices. The small fraction of operating costs may not affect whether to buy a car or not. Instead, it can influence buying a more or less efficient vehicle. Second, this approach may be difficult to explain for households buying used cars. However, the miles driven would not depend on whether the car is new or used. One remaining concern is that household or vehicle properties do not represent the population. According to Table 1.1, the dataset used in this analysis has a similar mean for each attribute. However, average income, MPG, and MSRP are higher than all data sets in the 2017 NHTS. Therefore, I conduct the robustness check to confirm the analysis results.

The goal of this paper is to analyze the VMT tax effect. For this analysis, I assume that the gasoline tax is fully passed on to consumers (Marion and Muehlegger (2011)), and the gasoline tax effect is the same as the gasoline price effect. The first assumption means that the VMT tax directly levied on road users can be analyzed similarly to the gas tax. The second assumption is the general assumption of the literature. One piece of literature opposing this assumption is Li et al. (2014). They suggest that a gasoline tax will be more effective in determining MPG or VMT than a tax-exclusive gasoline price. However, they report that the difference in gasoline price and tax impact on VMT is not statistically significant.

1.5.2. Identification. The structural model consists of two utilities of the household. The structural analysis releases the endogeneity problem (Bento et al. (2009), Gillingham (2011)). Also, the parameters of driving, $\tilde{\alpha}$ and λ, in the second period are identified through the variation in the operating cost. Identification of the driving cost effects benefits from a considerable variation in the operating cost. The data set contains the gasoline prices for the region CBSA or states, and the MPG varies across the 362 vehicles of choice set. The considerable variation in vehicle economy allows us to overcome the limited variation in the gasoline price in the cross-sectional data set and to estimate the consumer response to operating costs.

The parameters in the first period are identified through household and vehicle characteristics in addition to the exclusion restrictions in the second period. The operating cost per mile may be correlated with the vehicle's other attributes. The household could purchase a more efficient vehicle if it expects a higher gasoline price. However, 2016 gasoline prices have been relatively steady since 2015. It relieves the concerns about consumers' selection problems about vehicles. Also, fixed effects for the area, such as the Metropolitan Statistical Area(MSA) dummy variable, can prevent the selection issue by area. However, there may still be confounder variables. Linn (2016) criticizes that some studies may yield biased results when it includes vehicle characteristics or vehicle model fixed effects to account for omitted vehicle characteristics. Including variables of households' characteristics can relieve the concerns. The survey data has various characteristics of households, such as the number of workers in the household, having children or not, homeowner status, the average age of the household, race, education, and MSA. Additionally, including individual fixed effects in the vectors of $\tilde{\alpha}$ and θ addresses the unobserved characteristics that may be correlated with VMT.

The other concern is that fuel economy may be correlated with other vehicles owned by the household (Linn (2016)). To address this concern, I include the interaction terms of the average operating cost and VMT of the other vehicles owned by the household with the operating cost.

1.5.3. Elasticities. The estimates are generated with 40,000 iterations of the Gibbs sampling algorithm, discarding the first 30,000 iterations as burn-in. Among the last 10,000 estimations, only every 10th iteration is used for reported estimates[16]. All parameters are random coefficients, so the results provide the mean and standard errors for each coefficient across the household. By taking the Bayesian statistics procedures, the estimated posterior mean values for Θ are listed in Table 2.A.1 in Appendix 1.B.2.

[16]Every 10th iteration is used for calculating the average estimation results such as elasticities, likelihood, and variance, but I take every 200th iteration to obtain the results of parameters for the sensitivity analysis to reduce the computational burden.

Table 1.3 reports the posterior mean elasticities from the estimate results[17]. I use the point estimator with 50 iteratively simulating procedures to examine the elasticities. The mean of the vehicle price elasticity of car ownership for all vehicles is -1.97. This result falls within the range of the elasticities for new cars in Bento et al. (2009). The operating cost elasticity of car ownership is -0.01 for all households and vehicles. It is much smaller in absolute magnitude compared to the literature, Goldberg (1998), which provides -0.5 for the elasticity. It may be because the data in this analysis focuses on vehicles purchased more recently from 2016 to 2017 when the vehicle's fuel economy has been improved, and it does not include outside options. The last result in the table is the VMT elasticity with respect to operating costs. The VMT elasticity is -0.12 for all vehicles. It falls within the range of the literature (Li et al. (2014), Langer et al. (2017)). According to previous literature, the corresponding estimates range from -0.02 to -0.07 for short-run elasticity. Without specific mentions about the period, it has been in a range of -0.01 to -0.58 since 2007 in the US (Goetzke and Vance (2021), Small and Van Dender (2007)).

Table 1.4 shows the heterogeneity of the VMT elasticities over the household characteristics and vehicle types. The household having children, working, and living in a rural area has less VMT elasticity than those without children, retired, and living in an urban area. It implies that they barely respond to the operating cost change. Across the income, the higher-income households tend to have less VMT elasticity than the lower-income group. By the vehicle types, a van and a pickup truck have less elasticity than other vehicles. These results by vehicle types are consistent with the results by household characteristics. Households with children tend to purchase a van rather than a compact car. Also, pickup trucks are primarily task related. Across fuel types, EVs have higher VMT elasticity than other fuel-type vehicles. It may be because households considering the operating cost more tend to buy EVs.

[17]The definition of each elasticity is provided in Appendix 1.A.2

Table 1.3. **Posterior Mean Elasticities with Average Estimates**

	Car ownership elasticity wrt car price	Car ownership elasticity wrt operating cost	VMT elasticity wrt operating cost
Elasticities	-1.967	-0.009	-0.115

Table 1.4. **VMT Elasticities w.r.t Operating Cost by Attributes**

		By Household Characteristics			
Child	No child	work	retired	Urban	Rural
-0.054	-0.145	-0.087	-0.267	-0.116	-0.110
		By Income			
$0<inc<$15k	$15k<inc<$35k	$35k<inc<$50k	$50k<inc<$75k	$75k<inc<$125k	$125k<inc
-0.117	-0.177	-0.161	-0.147	-0.103	-0.077
		By Vehicle Types			
car	van	SUV	pick-up truck		
-0.128	-0.094	-0.116	-0.057		
		By Fuel Types			
EV	ICE	Hybrid			
-0.771	-0.102	-0.352			

1.6. Simulation Results

This section conducts several counterfactual analyses to evaluate switching the tax policy from a gasoline to a VMT tax. As mentioned above, the federal gasoline tax has been stuck at 18.4 cents per gallon since 1993. The federal government is considering introducing a VMT tax to replace a gasoline tax. It is, therefore, of interest to examine the welfare change of the policy shift from a gasoline tax to a VMT tax. The primary analysis keeps government revenue the same. Also, the welfare analysis focuses on changes in consumer surplus. This part uses the utilization utility function and the VMT demand for the counterfactual analysis to quantify the welfare impacts of the VMT tax. It focuses on extrapolating the short-term effect of the policy shift on consumer surplus. The VMT tax is designed to achieve the same government revenue as the gasoline tax. The short-run consumer surplus change is defined as:

$$E[\Delta U_{ijt}] = E[U_{2,ijt}(z_{ij}^{\alpha}, c_{ij}^{1})] - E[U_{2,ijt}(z_{ij}^{\alpha}, c_{ij}^{0})]$$

where other variables and parameters are as defined in section 1.3.2. The expectation of the change in consumer surplus is integrated over η_{ijt}. The expected consumer surplus change is the average of all households' consumer surplus changes when the policy shifts. Note that the original operating cost, c_{ij}^{0}, and the counterfactual operating cost, c_{ij}^{1}, vary across the household because the households have different vehicle efficiency and gasoline or electricity prices. If we convert the policy from a gas tax to a VMT tax, c_{ij}^{0} is a gas tax, and c_{ij}^{1} is a VMT tax.

There are three scenarios to evaluate the distributional effects of introducing a VMT tax. The initial simulation is a revenue-neutral VMT tax to generate the same government revenue as the current gas tax. For the second scenario, the incremental gasoline and VMT taxes are estimated to generate an additional 10% government revenue per year. Rather than exploring the effect of the VMT tax to cover the tax shortfall, the second scenario evaluates the consistency of the distributional impact of the VMT tax in both cases of sustaining or increasing government revenue. The last analysis considers gradual EV share growth from around 3% up to 10%. One of the forecasts suggests that EV share will be 7% in the market by 2030. It is, therefore, of interest to perform a sensitivity analysis of adopting VMT tax as EVs grow up to 10%. This analysis reports the private welfare changes from the policy shift as EV penetration grows[18].

The policy shift has a disparate impact on the individual based on their attributes. Each scenario compares the VMT and gas tax effects on the consumer surplus change per vehicle a year. The consumer surplus in the first two scenarios is examined by vehicle fuel efficiency, region(states and census), income, urban or rural, having children or not, and working or retired to assess the private welfare distributional impacts of the policy shift. Also, the last analysis provides how the welfare impacts of the VMT tax differ with the level of EV share in the market compared to a gasoline tax. It classifies the fuel types as non-EVs (ICEs and conventional Hybrids) and EVs since conventional

[18]The 2017 NHTS data shows that during 2010-2017, hybrids' shares for each year decreased from 4.4 % to 2.7%, while EV shares increased from 0.1% to 2.4%. Hence, the sensitivity analysis only considers the EV share increase in the market.

Hybrids mainly use gas for driving. It allows us to focus on the effects of EV growth by simplifying the analysis.

Since this paper aims to study the tax policy shift effect on the surplus changes by attributes and not examine the heterogeneity preference of the utility, the following sensitivity analyses use the average of point estimators without iteratively simulating. It reduces the computational burden and has similar results using the iterative simulation. The household is assumed that they do not change their vehicles in response to the tax change in the short run. Also, gas and VMT taxes are assumed to have the same behavioral response if they generate the exact change in operating costs. That is, households consider the cost of tax, not the type of tax.

1.6.1. Baseline Simulation. The baseline simulation provides the consumer surplus changes from the policy shift to a VMT tax to collect the same government revenue as the gasoline tax. The revenue-neutral VMT tax is numerically estimated by computing the miles driven with the utilization function at the operating cost, which generates the same government revenue. The households are assumed to keep their vehicle choice the same in response to the tax shift in the short run. The small value of the operating cost elasticity of car ownership convinces us that this assumption is reasonable and that long-term results are expected to be similar to the short-term results in this paper. The revenue-neutral VMT tax is 0.74, less than the tax suggested in McMullen et al. (2010). That is because this study considers the EVs, which have not paid the gasoline tax, the average MPG is higher than the literature, and focuses only on the federal gasoline tax, 18.4 cents per gallon, replaced with a VMT tax. McMullen et al. (2010) provides a revenue-neutral flat VMT tax of 1.2 cents per mile as the replacement of the fuel tax of 24 cents per gallon. They only examine the households in Oregon, assume an average fuel efficiency of 20 MPG from the vehicles, and do not estimate the miles driven on individual vehicles to calculate the revenue-neutral VMT tax. Meanwhile, this study assumes three fuel-type vehicles: ICE, Hybrid, and EV. The average MPG is 26.0 over all data sets used in this analysis. This analysis focuses on the current federal gasoline tax, 18.4 cents per gallon, replaced with a VMT tax of 0.74 cents per mile.

A VMT tax gives higher household benefits on average if the sum of miles driven under a VMT tax is equal to or larger than that of driving under a gasoline tax, according to section 1.3.1. The change in total driving is close to zero in this analysis. Specifically, converting to the VMT tax creates a slightly positive consumer surplus, around \$2 a year on average across all vehicles. The baseline results are offered in Table 1.5.

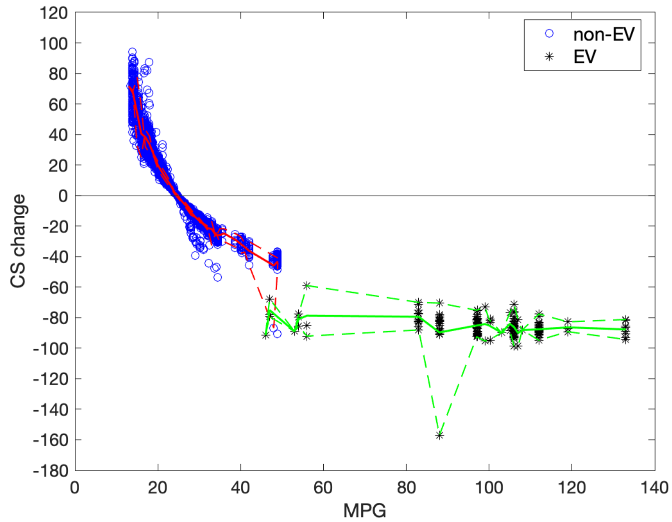
The marginal utility from (1.6) is:

$$MU_2 = \frac{\partial U_2}{\partial c} = \frac{\alpha \lambda c}{\zeta_{v,c}} \tag{1.12}$$

where $\zeta_{v,c}$ is the VMT elasticity with respect to the operating cost. i, j is suppressed to simplify the notation. The consumer surplus change from the tax policy shift would occur through three components: the households' fuel efficiency, the operating costs, and the VMT elasticity with respect to the operating cost. The revenue-neutral VMT tax reduces(increases) the operating costs of households who own less(more) fuel-efficient cars. The higher the operating cost and the lower the elasticity, the greater the marginal utility. The positive consumer surplus, as a result, is because households with less fuel-efficient cars tend to have lower elasticity, and the operating cost of EVs is much lower than that of other fuel-type vehicles.

Figure 1.1 shows the heterogeneity in the net consumer surplus change by the household's different MPG vehicles in the dataset. The average change in consumer surplus is only \$2 per vehicle per year, but given that there are more than 280 million registered cars, total consumer surplus is not negligible. Also, the distributional effect is more pronounced. Based on the average MPG, inefficient vehicles benefit up to about \$90 per year, while efficient vehicles deteriorate up to \$100 per year, ignoring extreme outliers. Individual households in each MPG are likely to have different benefits or losses depending on vehicle miles driven and operating cost elasticity. All

Figure 1.1. Change in Net Consumer Surplus of VMT Tax versus Gas Tax for Different MPGs when Collecting the Same Government Revenue ($/year/vehicle)



Notes: Net consumer surplus is defined as the change in consumer surplus from the expected utility under the gasoline tax to the expected utility under the VMT tax, where all tax rates keep the same government revenue.

MPGe of EVs are over 45. If the policy changes to a VMT tax, the EV holders would lose an average of $80 per year because they have not paid the gasoline taxes.

Figure 1.2 and 1.4 provide the distributional effects over the state and census division, respectively. Even if the same federal VMT tax is levied instead of the gasoline tax, some states would have positive consumer surplus change, while others would be worse off. It mainly depends on the average MPG, the VMT elasticity, and vehicle miles traveled in each state[19]. Interestingly, the map is quite similar to the map of electric vehicle share in the US in Figure 1.3. California, Washington DC in the District of Columbia, Boston in Massachusetts, and Vermont have a larger share of EVs than other states. They also are worse off from the policy shift to the revenue-neutral VMT tax. The states in the middle of the US tend to benefit from the federal tax shift. Figure 1.4 is more pronounced, showing that regions with higher MPG vehicles are worse off and regions with lower

[19]I exclude the ten states with the fewest samples and make them white in the figures presenting distributional effects over the states.

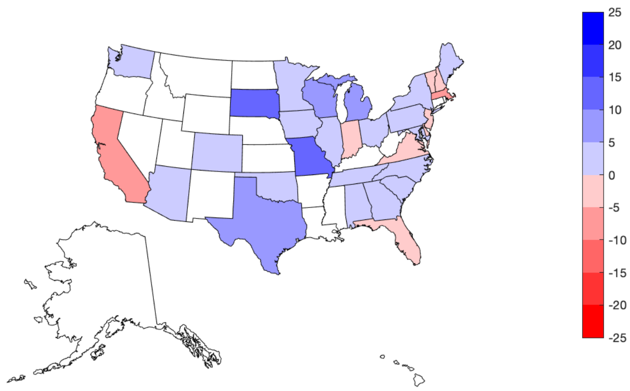
MPG vehicles are better than before introducing the VMT tax. The average MPG in the Pacific is 30, and the average in New England is 27. These areas are worse off. The average MPG declines towards the center of the US. The average MPG in west north central and west south central are 24 and 25, respectively. These areas obtain gains from the policy shift. The sign of consumer surplus change primarily hinges on the average MPG.

Figures 1.5 to 1.7 indicate the same counterfactual analysis results by several partitions of household characteristics over the income groups. The households living in rural areas or with children get more gains than others. The working or retired household is not that different, but the working household has a bit larger benefit than the retired household. In addition, each partition has similar patterns over the income. The lower-income household has more losses, while the higher-income household has more gains than before the policy shift. That is because higher-income household has more luxury cars with lower MPG. It implies that the VMT tax is slightly more regressive than the gas tax.

The counterfactual analysis in this section represents the average consumer surplus of a single vehicle in each specified group. However, around 40% of households have two cars, which is larger than the share of households having a single car. It is of interest to examine the portfolio effects of the policy shift. Table 1.6 shows the consumer surplus change having two vehicles. Based on fuel economy, vehicles are classified into three types: Low MPG, High MPG, and EVs. A low (high) MPG is a vehicle with a lower (higher) fuel economy than the average MPG in this data set. EVs include only electric vehicles, as defined in this paper. If the holding vehicles are all low fuel efficient, the households obtain $33 per year from the policy change. Household having both low and high MPG vehicles obtain slightly positive benefits. As long as households own EVs, consumer surplus is always negative due to the new tax imposition.

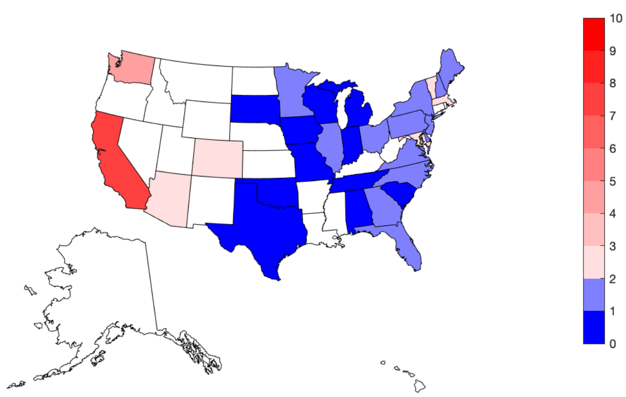
1.6.2. Sensitivity Analysis: Government Revenue Growth. The stuck federal gasoline tax leads to discrepancies between tax revenues and expenditures. It would require a gasoline tax increase to cover the shortfall. This analysis focuses on the distributional impact of the incremental

FIGURE 1.2. Change in Net Consumer Surplus of VMT Tax versus Gas Tax by State when Collecting the Same Government Revenue ($/year/vehicle)



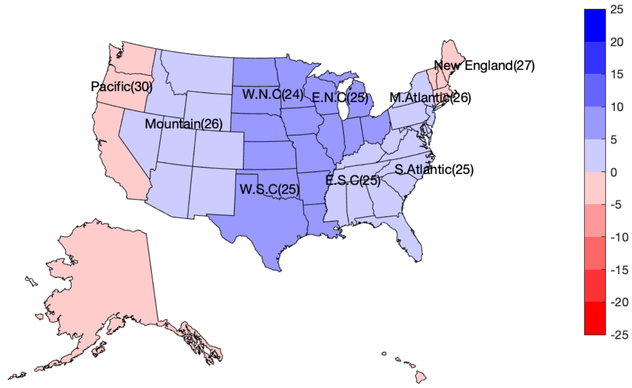
Notes: Net consumer surplus is defined as the change in consumer surplus from the expected utility under the gasoline tax to the expected utility under the VMT tax to keep the same government revenue. White on the map indicates areas ignored in the analysis because of few sample.

FIGURE 1.3. Electric Vehicle Sales Market Share(%) by State for the year 2019



Notes: The data source is EV Adoption. White in the map is the same areas ignored in the analysis because the 2017 NHTS sample was few.

Figure 1.4. Change in Net Consumer Surplus of VMT Tax versus Gas Tax by Census Division when Collecting the Same Government Revenue ($/year/vehicle)



Notes: Net consumer surplus is defined as the change in consumer surplus from the expected utility under the gasoline tax to the expected utility under the VMT tax to keep the same government revenue. The numbers in parentheses are the average MPG for each area.

tax to increase government revenues instead of increasing revenues to cover a projected shortfall. It shows the consistency of the distributional effects of the VMT tax and the plausible impact of revenue growth under the new tax. The tax is designed to increase government revenue by 10% from the current gasoline tax. Under the gasoline tax policy, the tax would be 20.26 cents per gallon. If we are under the VMT tax, the tax to increase the government revenue by 10% would be 0.82 cents per mile. The net consumer surplus change is designated as the VMT tax effect. The change in consumer surplus is computed as a result of the incremental tax when government revenues increase by 10% compared to the baseline tax (the revenue-neutral tax). Then the net consumer surplus of the VMT tax is the change in the consumer surplus of the VMT tax minus the change in the consumer surplus of the gas tax. It compares the VMT tax impacts on the consumer to the gas tax when we increase the government revenue. The second column of Table 1.5 summarizes

FIGURE 1.5. Change in Net Consumer Surplus of VMT Tax versus Gas Tax by Rural/Urban and Income when Collecting the Same Government Revenue ($/year/vehicle)

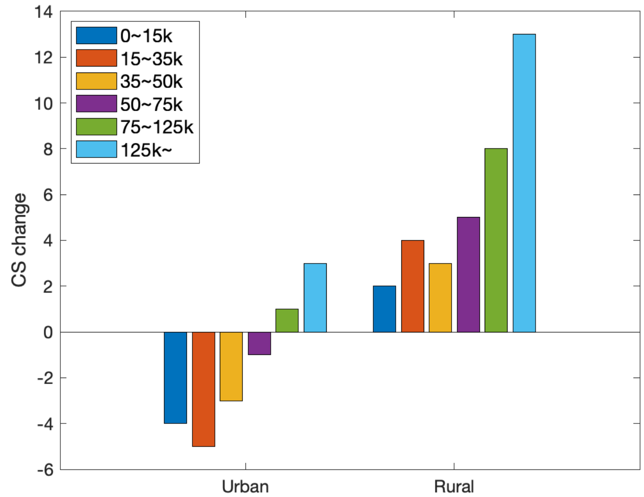
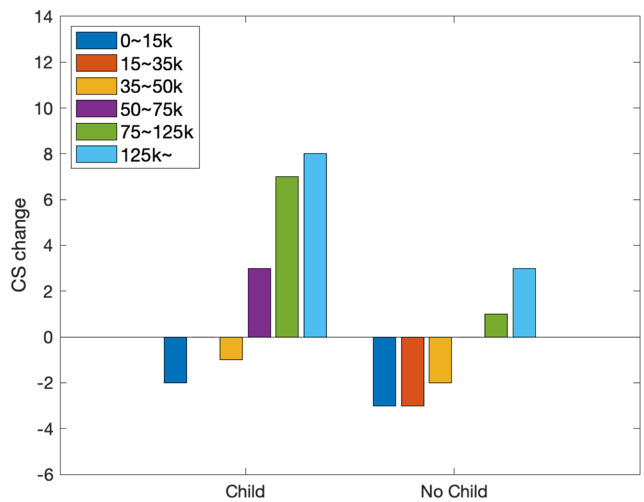
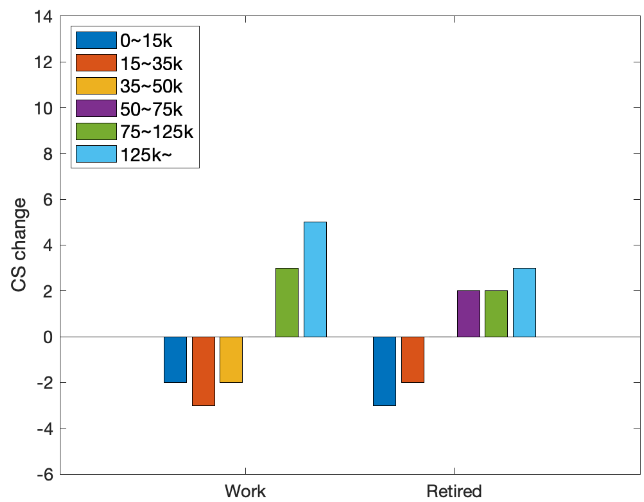


FIGURE 1.6. Change in Net Consumer Surplus of VMT Tax versus Gas Tax by Child/No Child and Income when Collecting the Same Government Revenue ($/year/vehicle)



Notes: Net consumer surplus is defined as the change in consumer surplus from the expected utility under the gasoline tax to the expected utility under the VMT tax to keep the same government revenue.

FIGURE 1.7. Change in Net Consumer Surplus of VMT Tax versus Gas Tax by Work/Retired and Income when Collecting the Same Government Revenue ($/year/vehicle)



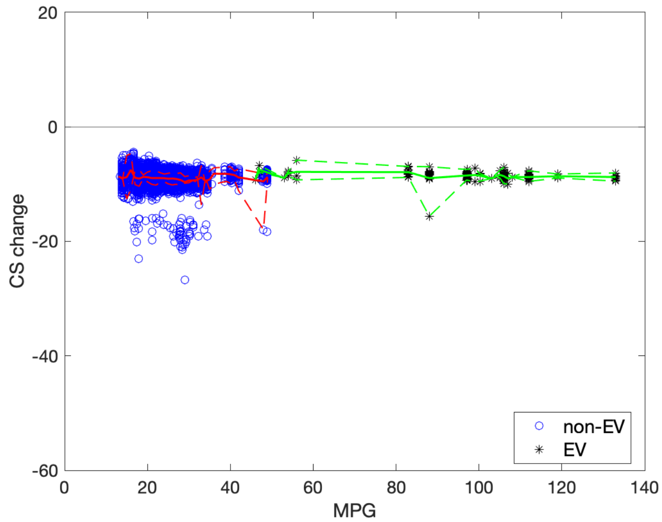
Notes: Net consumer surplus is defined as the change in consumer surplus from the expected utility under the gasoline tax to the expected utility under the VMT tax to keep the same government revenue.

the results. It is minor as $0.2 per vehicle per year, but it still positively affects the consumer on average.

Figure 1.8 and 1.9 show the consumer surplus change under VMT tax and gas tax when increasing government revenue by 10%, respectively. The average effects of increasing the revenue under each tax are similar to around -$9 per year on average. However, the distributional effects are different. Increasing the tax under the VMT tax reduces consumer surplus evenly across all MPGs. The gas tax, on the other hand, reduces consumer surplus more as MPG is lowered. Additionally, it does not affect the EV holder at all. It could raise the fairness issue over the households.

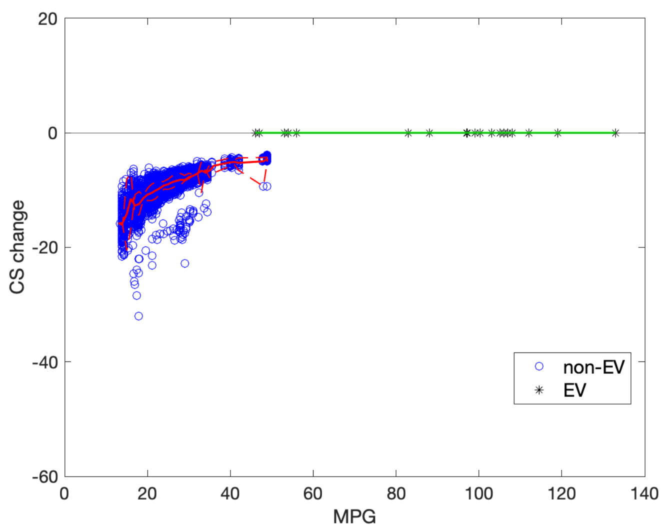
The heterogeneity in consumer surplus change also occurs over the states. Figure 1.10 and 1.11 indicate the consumer surplus change over states when increasing VMT tax and gas tax, respectively. It presents that the net consumer surplus from the VMT tax is more favorable in the

Figure 1.8. Change in Consumer Surplus of the VMT Tax for Different MPGs when Increasing Government Revenue by 10% ($/year/vehicle)



Notes: Consumer surplus is defined as the consumer surplus change from the expected utility under the revenue-neutral VMT tax to the utility under the VMT tax to increase the government revenue by 10%.

Figure 1.9. Change in Consumer Surplus of the Gasoline Tax for Different MPGs when Increasing Government Revenue by 10% ($/year/vehicle)



Notes: Consumer surplus is defined as the consumer surplus change from the expected utility under the revenue-neutral gas tax to the utility under the gas tax to increase the government revenue by 10%.

Table 1.5. **Net Consumer Surplus of VMT Taxes versus Gas Taxes**

	The Same Government Revenue	**Increase Government Revenue by 10%**
VMT tax (cent/mile)	0.74	0.82
Gas tax (cent/gallon)	18.40	20.26
Consumer Surplus change ($/year/vehicle)		
Total Average	2.0	0.2
Urban	0.3	0.0
Rural	7.8	0.8
		0.0
Child	6.0	0.6
No Child	0.9	0.1
		0.0
Work	2.3	0.2
Retired	1.0	0.1
income<$15,000	-2.8	-0.3
$15,000<income<$35,000	-2.4	-0.2
$35,000<income<$50,000	-1.5	-0.1
$50,000<income<$75,000	0.8	0.1
$75,000<income<$125,000	2.6	0.3
$125,000<income	4.7	0.5

Notes: Net consumer surplus is defined as the change in consumer surplus from the expected utility under the gasoline tax to the expected utility under the VMT tax.

Table 1.6. **Portfolio Effect of Two Vehicles on Net Consumer Surplus of VMT Tax versus Gas Tax when Collecting the Same Government Revenue**

($/year/vehicle)	Low MPG	High MPG	EVs
Low MPG	33.3	1.8	-69.3
High MPG	1.8	-29.6	-100.7
EVs	-69.3	-100.7	-171.8

Notes: Net consumer surplus is defined as the change in consumer surplus from the expected utility under the gasoline tax to the expected utility under the VMT tax.

Central US. The VMT tax increase similarly reduces consumer surplus for the state, while the gas tax increase reduces more central US, which has lower MPG than other regions.

Across household characteristics, the gas tax change also affects consumers differently. Figures 1.12 to 1.14 show that the VMT tax reduces the consumer surplus of the households living in rural areas, having children and working less than the other groups. Irrespective of these groups, lower-income households tend to be worse off with tax increases under VMT tax policies compared to the gas tax. These results are consistent with the distributional effects of the revenue-neutral VMT tax and reconfirm that the VMT tax is more regressive than the gas tax.

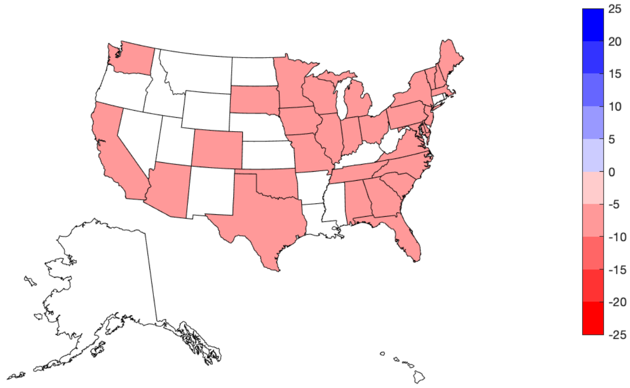
1.6.3. Sensitivity Analysis: EV Share Growth. This section conducts sensitivity analysis by increasing EV shares up to 10% and keeping the government revenue constant. In this data set, the miles driven by EVs tend to be less than other fuel types. Since there is no evidence that EV share affects driving patterns, I assume that households' preferences for choosing mileage do not change[20].

Table 1.7 summarizes the consumer surplus change as EV penetration grows under the VMT tax and gas tax. The gas tax requires raising the tax even to keep the government revenue as EVs grow. That is because a high proportion of electric cars means a high proportion of drivers who do not pay taxes. However, the VMT tax does not require political action to sustain government revenue. Figure 1.15 clearly shows the comparison of the tax charge required to sustain the government revenue by the EV share. It leads to little change in consumer surplus under the VMT tax. Meanwhile, the gasoline tax further reduces the change in consumer surplus caused by the growth of electric vehicles. Therefore, the net consumer surplus from introducing a VMT tax, defined as the change in consumer surplus from the risen VMT tax minus the change from the risen gas tax, increases to \$8.2 per year as the share of electric vehicles rises to 10%.

Figure 1.16 displays the net consumer surplus change of the sensitivity analysis by EV shares and vehicle fuel types. The EV holder's net consumer surplus change from adapting VMT tax is around zero. Meanwhile, the ICE holder's net consumer surplus increases as the EV share increases. EV holders would not pay a gasoline tax, but all drivers are evenly charged a VMT tax after the tax shift. It reduces the burden of the ICE holders; hence their net benefits increases. On average, the total net consumer surplus increases progressively as EV penetration increases. An

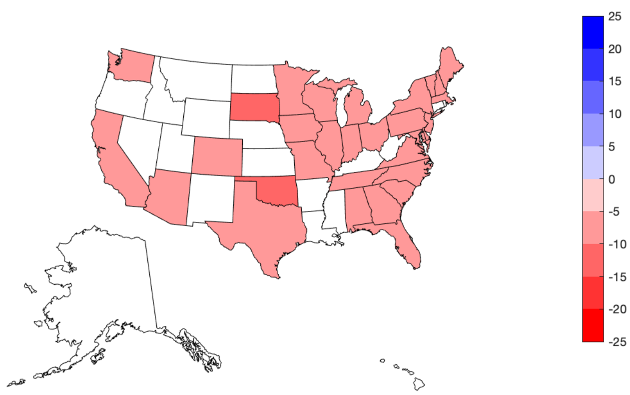
[20]Norway has the highest share of electric vehicles. There is a considerable gap in Norway between the miles driven by EVs and ICEs. As the share of electric vehicles increases, the miles driven by electric vehicles have increased, but still less than diesel, Norway's most popular internal combustion engine. Since the gap in the US is not as large as in Norway, this analysis assumes that the mileage by vehicle type is stable.

Figure 1.10. Change in Consumer Surplus of the VMT Tax by State when Increasing Government Revenue by 10% ($/year/vehicle)



Notes: Consumer surplus is defined as the change in consumer surplus from the expected utility under the revenue-neutral VMT tax to the expected utility under the VMT tax to increase the government revenue by 10%.

Figure 1.11. Change in Consumer Surplus of the Gasoline Tax by State when Increasing Government Revenue by 10% ($/year/vehicle)



Notes: Consumer surplus is defined as the change in consumer surplus from the expected utility under the revenue-neutral gas tax to the expected utility under the gas tax to increase the government revenue by 10%.

FIGURE 1.12. Change in Net Consumer Surplus of VMT Tax by Rural/Urban and Income when Increasing Government Revenue by 10% ($/year/vehicle)

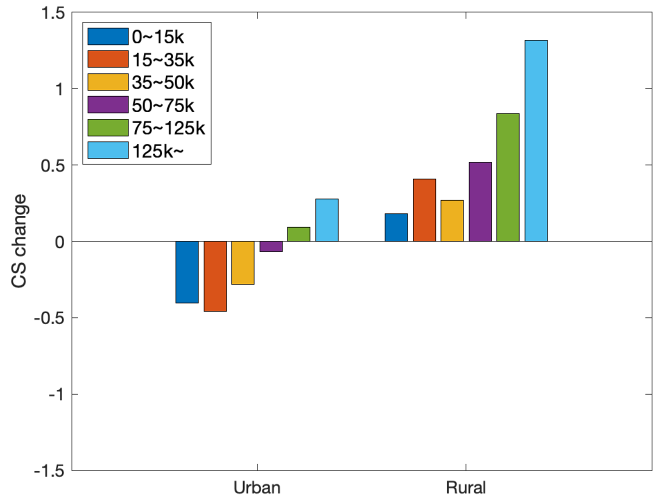
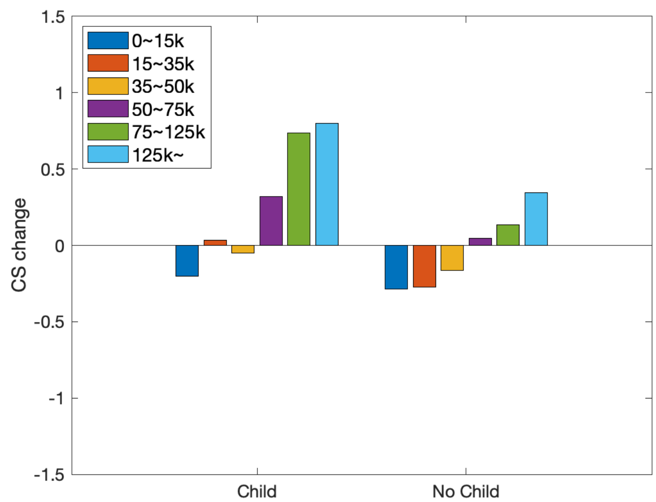
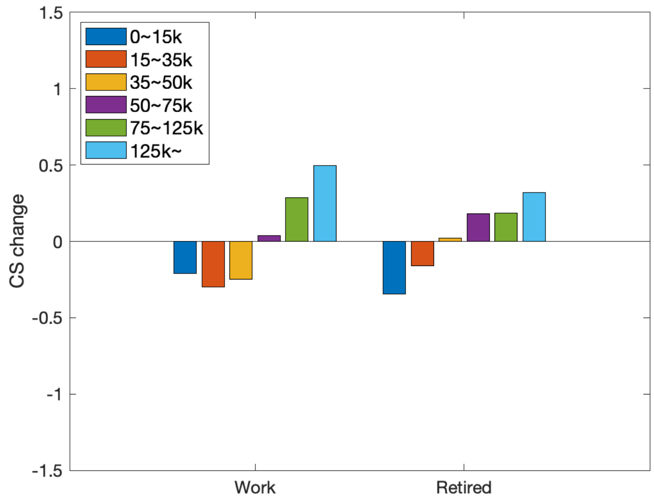


FIGURE 1.13. Change in Net Consumer Surplus of VMT Tax by Child/No Child and Income when Increasing Government Revenue by 10% ($/year/vehicle)



Notes: The net consumer surplus is the difference between the change in consumer surplus from the VMT tax and the change in consumer surplus from the gas tax. The change in consumer surplus for both tax policies is caused by raising the tax from the revenue-neutral tax rate to a rate that increases government revenue by 10%.

FIGURE 1.14. Change in Net Consumer Surplus of VMT Tax by Work/Retired and Income when Increasing Government Revenue by 10% ($/year/vehicle)



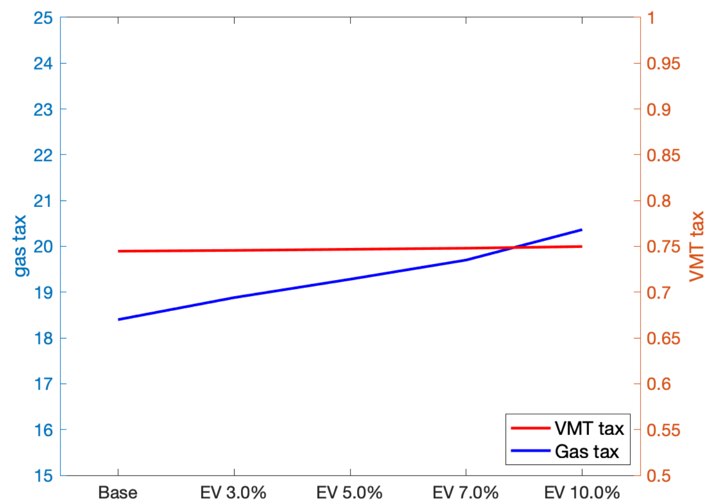
Notes: The net consumer surplus is the difference between the change in consumer surplus from the VMT tax and the change in consumer surplus from the gas tax. The change in consumer surplus for both tax policies is caused by raising the tax from the revenue-neutral tax rate to a rate that increases government revenue by 10%.

increase in EV market share of about 5% brings an additional benefit, which is twice the benefit of adopting a VMT tax when EV market share changes are not taken into account.

Figure 1.17 shows the distributional effect over fuel efficiency when EV share is 10%. ICE holders have a significant change in net benefits. Owners of less efficient vehicles have gained from the VMT tax. Also, all ICE holders have some positive surplus. However, the net benefit to EV holders is negligible.

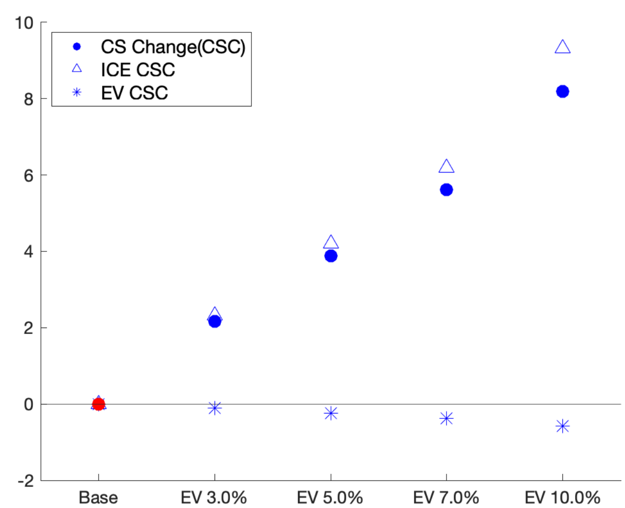
One concern with this sensitivity analysis is what types of vehicles will be replaced by EVs as EVs grow. I conduct the same analysis assuming that EVs substitute cars above 25 MPG and assuming vans, pick-up trucks, and SUVs are not replaced with EVs (Xing et al. (2019)). The result with the substitution assumption in Figure 1.18 is very similar to the results in Figure 1.17, which is the result without the assumption.

FIGURE 1.15. Estimated VMT Tax(cent/mile) and Gas Tax(cent/gallon) Required to Collect the Same Government Revenue under Different EV Share Assumptions



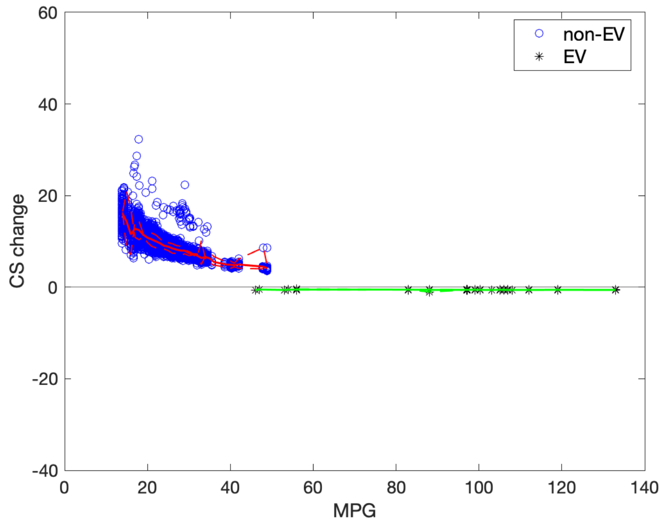
Notes: The base case for EV share is around 1%. The revenue-neutral tax rate for different EV shares is estimated by resampling to satisfy the EV share assumptions.

FIGURE 1.16. Predictions of Net Consumer Surplus Change by Fuel Types under Different EV Share Assumptions ($/year/vehicle)



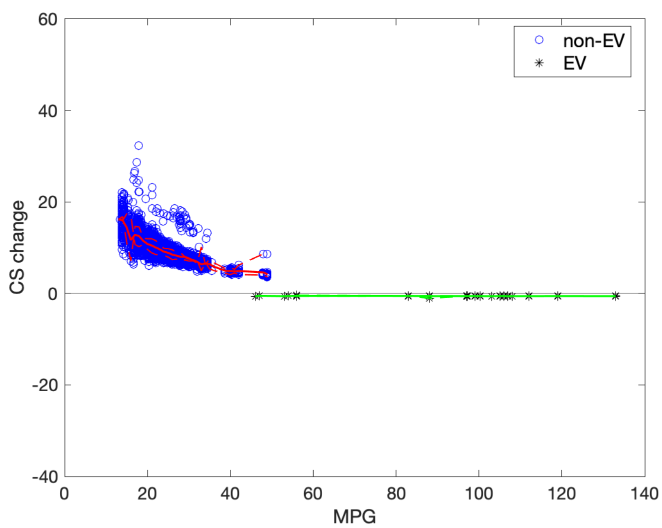
Notes: The net consumer surplus change is the difference between the change in CS from the VMT tax and the change in CS from the gas tax. The change in CS for both tax policies is caused by changing the tax from the revenue-neutral tax rate with the base case of EV share around 1% to the revenue-neutral tax rate with each different assumption of EV share.

FIGURE 1.17. Change in Net Consumer Surplus of VMT Tax versus Gasoline Tax for Different MPGs assuming 10% EV share ($/year/vehicle)



Notes: The net consumer surplus change is the difference between the CS change from VMT tax and the CS change from gas tax. The change in CS for both tax policies is caused by changing the tax from the revenue-neutral tax rate with the base case of EV share around 1% to the revenue-neutral tax rate with 10% EV share.

FIGURE 1.18. Change in Net Consumer Surplus of VMT Tax versus Gasoline Tax for Different MPGs assuming 10% EV share with substitution assumption for EVs ($/year/vehicle)



Notes: The substitution assumption for resampling is described in the text.

TABLE 1.7. **Net Consumer Surplus Change as EV Share Increases when Collecting the Same Government Revenue**

	EV Share			
	3%	5%	7%	10%
under VMT tax				
CS Change ($/year/vehicle)	-0.2	-0.3	-0.5	-0.7
Tax (cent/mile)	0.75	0.75	0.75	0.75
under Gas tax				
CS Change ($/year/vehicle)	-2.3	-4.2	-6.1	-8.9
Tax (cent/gal)	18.88	19.28	19.7	20.37
Net CS change ($/year/vehicle)	2.2	3.9	5.6	8.2

Notes: The change in consumer surplus for each tax is the change in consumer surplus from expected utility under the revenue-neutral tax without increasing the EV share to the expected utility under the tax with increasing the EV share. Net consumer surplus is defined as the change from the expected utility under the gasoline tax to the expected utility under the VMT tax for each EV share. Therefore, the net consumer surplus change implies the impact of the VMT tax introduction in each case.

1.6.4. Robustness. Three assumptions are considered for robustness. One is that the household expects the future gasoline price to be close to the current gasoline price. The alternative assumption is to use the actual future price. To verify robustness, I use the forecasted annual EIA gasoline price for January 2016. The future price of gasoline is applied to the utility in the first period, and the current price is applied to the second period.

The second assumption is that households consider the five-year depreciation rates of the vehicle when expecting the resale price. The alternative assumption is that ten-year depreciation rates are considered for the expected resale price in the first period.

The last assumption is that the average 10-year T-Bills during 2016-2017 are used to calculate the opportunity cost of the vehicle price per year. If households consider using a loan to own a vehicle, the opportunity cost of purchasing a vehicle may be higher than a 10-year T-bill. Instead, the average interest rate on new car loans for 60 months from 2016 to 2017 is used to examine the opportunity cost.

Three alternative assumptions have similar results. In all cases, the car ownership elasticity with respect to the rental prices and the car ownership elasticities with respect to operating costs are persistent. VMT elasticities with respect to operating costs tend to be slightly higher than the result with the primary assumption. However, the total consumer surplus is still slightly positive, and the sensitivity analyses also give similar results.

The other concern is the data limitation. This analysis only takes new vehicle purchases for around one year. It may underestimate or overestimate the VMT tax effects. Because the CAFE standard regulates the automobile economy, the sensitivity analysis results may underestimate the benefits of the VMT tax over the gas tax. CAFE requires manufacturers to meet an average of 37 MPG for model years 2021 through 2026. As vehicle fuel efficiency improves, the welfare from replacing a gas tax with a VMT tax will become more prominent. Also, the data set is from 2016 - 2017, which includes more fuel-efficient vehicles than the population; hence, it may overestimate the VMT tax benefit compared to the gas tax. For robustness and qualifications, I relax the two limitations discussed above. First, it provides an alternative analysis of a 5% improvement in fuel economy for the ICEs. It also performs the same analysis by reducing the fuel economy of the ICEs by 5% so that the average MPG is similar to the average MPG of all datasets from the 2017 NHTS. In both cases, it provides little difference in the results of elasticities. The total consumer surplus is similar and maintains consistent results within small changes in magnitude.

1.7. Conclusion

This paper examines the distributional effects of the policy shift from a gasoline tax to a VMT tax by focusing on the consumer surplus in the short term. It takes the two-period utility function jointly modeling a vehicle and utilization decisions and applies a Bayesian statistical perspective employing a Gibbs sampler estimation procedure. This approach takes advantage of estimating the random parameters of a large dataset of the vehicle choices and subsequent decisions of miles driven. It also allows the unobserved heterogeneous preference of households. The results of the estimates provide the heterogeneity in elasticities among vehicles and household types, which explore the distributional impacts of the policy shift by the attributes. Finally, the sensitivity analysis explains the effect of policies on consumer surplus as electric vehicle penetration increases in line with growth expectations.

The estimates find that households heterogeneously react when having vehicle and utilization choices in response to changes in the operating costs of the vehicles. Considering the current average operating cost, each cent-per-mile increase in the operating cost reduces driving by about 1 percent and the probability of purchasing the vehicle by around 0.1 percent on average. The utilization decisions have more heterogeneous and significant responses from the change in operating cost than the vehicle choices. It implies that, in the short term, the household responds to the operating cost by affecting their miles driven rather than changing a vehicle. Also, long-term analyses that allow vehicle changes may yield similar results.

The empirical analysis results have three implications for policymakers. First, the VMT tax is more efficient than the gas tax. The revenue-neutral VMT tax drives a positive consumer surplus to a modest amount, suggesting that conversion of tax policy can improve private welfare. Scenarios set equal government revenues. In addition, the externalities of driving an electric vehicle are not explicitly less than ICE, according to various disputes. Given the same government revenues and arguments about the externalities, private welfare benefits imply social welfare benefits as long as the total mileage under the two tax policies is not very different.

Also, state policymakers should consider the disparate impacts of introducing a federal VMT tax. The heterogeneity of effects primarily reflects differences in vehicle efficiency. The counterfactual analysis indicates that winners and losers in regions affected by the same amount of policy change will differ significantly depending on the average MPG for those regions. The revenue-neutral VMT tax, 0.74 cents per mile, replaces the current federal gas tax, 18.4 cents per gallon, equally in all states, affecting operating costs differently depending on the MPG. Policymakers in each state may want to consider the impact of federal tax changes on that state and respond differently for their purposes. For example, a negative consumer surplus in the state implies that the state's driving miles have decreased due to a change in federal policy. When the state policy is to reduce driving on the road, a policy shift of the federal gasoline tax may support the outcome of the state policy to some extent.

Lastly, the sooner the policy change to VMT tax, the less consumer surplus reduction, and the earlier discrepancy between government revenues and expenditures will be avoided. The sensitivity analysis of EV share in the market reports that EV share significantly impacts changes in average consumer surplus. The growth of EV share leads to an increase in the net consumer surplus change of the VMT tax explicitly. In particular, if the EV market share rises to around 5%, an additional tax conversion benefit occurs that is about twice as large as when the EV market share change is not considered. It implies that policymakers need to consider EV penetration rates to determine the timing of policy changes. Otherwise, the opportunity cost of policy transition will surge. Also, a VMT tax could dominate a gas tax as it can reduce political actions such as tax increases due to improved fuel efficiency in the market. As EVs increase, the gasoline tax will have to rise to keep government revenues up, but the VMT tax will remain at a similar rate. The findings suggest a motive for shifting to a VMT tax to address the inefficiency of the gas tax and the lack of government revenue from the gas tax as the average MPG is improved.

This work has two limitations. First, the 2017 NHTS data set includes a small share of EV purchases. Hence, the model in this paper does not distinguish the fuel type in the modeling. Instead, the random coefficients are used to incorporate the heterogeneity for the different fuel types. Nonetheless, it would be worth modeling and estimating the parameters for EV purchasing separately in future work. In addition, the model only considers the operating cost of driving. One of the challenges of adopting a VMT tax is keeping track of the miles driven for tax purposes. There is no data to quantify the tracking cost, and the discussion is out of the purpose of this paper. In the future, however, it would be interesting to include the cost of introducing a VMT tax in the cost of policy change to determine its impact on policy outcomes.

Appendix

1.A. Derivation

1.A.1. Expected Utilty Function for Utilization. At the optimal choice, the utility function for utilization is derived from plugging the optimal choice of driving in (1.7) in the utility function (1.6). Then, the optimal utility in the second period is as follows:

$$
\begin{aligned}
U_{2,ij} &= \frac{1}{\alpha_{ij}}(M^*_{ij} - \frac{1}{2\lambda_i}M^{*2}_{ij}) - c_{ij}M^*_{ij} \\
&= \frac{1}{\alpha_{ij}}((\lambda_i - \alpha_{ij}\lambda_i c_{ij}) - \frac{1}{2\lambda_i}(\lambda_i - \alpha_{ij}\lambda_i c_{ij})^2) - c_{ij}(\lambda_i - \alpha_{ij}\lambda_i c_{ij}) \\
&= \frac{\lambda_i}{2\alpha_{ij}}(1 - 2\alpha_{ij}c_{ij} + \alpha^2_{ij}c^2_{ij})
\end{aligned} \tag{1.13}
$$

The risk-neutral consumers take an expectation of the utility function as follows:

$$
\begin{aligned}
E[U_{2,ij}] &= \frac{\lambda_i}{2\alpha_{ij}} - \lambda_i E[c_{ij}] + \frac{\alpha_{ij}\lambda_i}{2}E[c^2_{ij}] \\
&= \lambda_i(\frac{1}{2\alpha_{ij}} - E[c_{ij}] + \frac{\alpha_{ij}}{2}(E[c_{ij}]^2 + var[c_{ij}]))
\end{aligned} \tag{1.14}
$$

The last equation in (1.14) is from the law of the random variable variance, the expectation of the square minus the square of expectation.

1.A.2. Elasticities. In Table 1.3, there are three elasticities.

The car ownership elasticity with respect to car price is defined as:

$$\zeta_{c,p} = \frac{\partial P_r/P_r}{\partial P^v/P^v} \tag{1.15}$$
$$where \quad P_r = \frac{exp(U_1)}{\sum_n exp(U_{1,n})}$$

To simplify the notation, I suppress i and j and define $S \equiv lnP_r$. Then, $\frac{\partial P_r}{\partial U_1} = e^s(1-e^s)$. By the chain rule, the elasticity is as follows:

$$\zeta_{c,p} = \frac{\partial P_r/P_r}{\partial P^v/P^v} = -e^s(1-e^s)(r-\delta_2(1-d))\frac{P^v}{P_r} \tag{1.16}$$

Similarly, and using the dominated convergence theorem, the car ownership elasticity with respect to operating cost is:

$$\zeta_{c,c} = \frac{\partial P_r/P_r}{\partial c/c} = -e^s(1-e^s)\delta_1\lambda(1-\alpha E[c])\frac{c}{P_r} \tag{1.17}$$

VMT elasticity with respect to the operating cost is as follows:

$$\zeta_{v,c} = \frac{\partial M/M}{\partial c/c} = -\frac{\alpha c}{(1-\alpha c)} \tag{1.18}$$

1.B. Data Description and Empirical Results

1.B.1. Data Description. The federal government and each state in the US provide tax credits or subsidies for purchasing new or even used EVs. The federal government offers a tax credit worth up to \$7,500 based on the battery capacity used to power the vehicle. State subsidies vary from state to state. Table 1.B.1 lists the subsidy for the alternative vehicles by state, provided by AFDC and each state's website. California, one of the US's largest EV markets, provides grants of up to \$5,000 from the Fueling Alternatives Vehicle Rebate program before 2009 and \$2,500 based on the income after 2010. Subsidies are applied to the price data by state, time, and MSRP to calculate the price of all vehicles in households' garages.

Table 1.B.2 and 1.B.3 show the data summary by the Census division and state. The summary in the tables suggests that the data used in this analysis is very similar to all data in 2017 NHTS.

TABLE 1.B.1. **Subsidy Valid for 2016-2017 by State**

Incentive by States	Period	Conventianal hybrid($)	PHEV($)	EV($)	Note
California	2010-	-	1000	2000	increased up to $2500 based on the income except for FCEV
Colorado	2017-2020		5000	5000	
Florida	2014.9-		700	1200	
Massachusetts	2014-		2500	2500	
Maryland	2014.7-2020.6		3000	3000	
New York	2017-		2000	2000	under MSRP$60,000, otherwise $500
Oregon	2003-2018	750	1500	2500	
Pennsylvania	2004-		500	750	
South Carolina	2012-2016	20% of federal tax credit	2000	2000	$667+$111 per kWh
Washington	2015-2018		6.5%	6.5%	sale tax exemption, https://afdc.energy.gov/laws/8260
Wisconsin	2018		500	500	

Notes: Sources are the Alternative Fuels Data Center and each state's website.

TABLE 1.B.2. **Summary Statistics: NHTS and Sample by Census Division**

	NHTS(2017)			Sample		
	Gas price	Average MPG	Average VMT	Gas price	Average MPG[a]	Average VMT
	$/gallon ($2021)	miles/gallon	miles	$/gallon ($2021)	miles/gallon	miles
Census Division						
New Egnland	2.5	24.8	12,149	2.5	27.3	13,259
Middle Atlantic	2.4	24.4	11,680	2.4	25.9	12,261
East North Central	2.5	23.7	12,490	2.5	24.7	13,461
West North Central	2.4	23.2	11,815	2.4	24.4	12,207
South Atlantic	2.4	24.1	12,466	2.4	25.1	13,635
East South Central	2.3	23.7	13,289	2.4	25.2	14,233
West South Central	2.1	23.6	12,402	2.1	24.5	13,296
Mountain	2.6	23.9	11,441	2.6	25.7	11,975
Pacific	3.0	26.5	11,593	3.0	29.8	12,576

Notes: Sources are described in the text. [a] The average MPG is the data after merging 2017 NHTS with Dataone.

1.B.2. Empirical Results. The estimated posterior mean values for Θ are listed in Table 2.A.1. The first-period utility is composed of the parameters, $\theta, \delta_1, \delta_2$ and μ. θ can be interpreted as the effect on the utility from the vehicle attributes the households own. The MSA fixed effect has various signs and magnitudes. The middle of the US tends to be positive coefficients, while the east of the US tends to be negative for just having a vehicle. Specific definitions of MSA are listed in Table 1.B.5. The horsepower, wheelbase, width, and height have positive signs, implying that having a larger car adds to the utility of just owning the vehicle. An SUV appears to have more value relative to a car, while a van or pickup truck does not add to the utility compared to a car. EV seems to have a very high value relative to ICE and Hybrid. It implies that owning an EV leads to a higher utility valuation as it is. Most coefficients of the brands have negative signs. It may be because, conditional on the vehicle size, type, and fuel types, most brands do not significantly contribute to the utility of owning the vehicle on average. δ_1 is the coefficient of the expected utility of the second period. It is positive, as expected, but the magnitude is relatively small. It implies that the households may consider the vehicle attributes more than driving when purchasing a vehicle. δ_2 is the coefficient of the expected resale price of the vehicle, and μ is the coefficient of the expected miles driven's effect on the resale price. As driving more, the expected resale price is reduced. However, the expected resale price is negative and does not add to the utility. It implies that a household may not significantly consider the expected resale price when buying a new car.

The second-period utility has $\tilde{\alpha}$ and λ as parameters. The vector of $\tilde{\alpha}$ includes household and vehicle attributes that affect the utility of driving. The interpretation of the estimated parameters is not simple in the utility function. Instead of focusing on the utility, I interpret the parameters by focusing on driving consumption. If the coefficient is positive, it will increase driving. As the households have more workers or children between 0-15 old, the household would drive more. According to the MSA size variables, the area with having much more population seems to drive less. It may be because congested areas reduce the utility of driving. The coefficient of horsepower-to-weight is negative, showing that the higher horsepower travels fewer miles than the lower horsepower. It implies that more powerful horsepower vehicles lead to higher utility in owning a vehicle but that vehicles do not appear to drive long distances. Conditional on having a child, households with a van seem to drive less than a car. ICE and Hybrid have negative coefficients. It means that conditional on the other attributes, ICE or Hybrid holders would decrease driving as the operating cost increases compared to EVs. Conditional on the other vehicle attributes, the higher-income households would drive more than the lower-income households. Also, as the other vehicles the households own have higher operating costs on average, the household drives more with the chosen vehicle. If the other vehicles in their garages have higher miles driven on average, the chosen vehicle also tends to drive more.

Table 1.B.3. **Summary Statistics: NHTS and Sample by State**

	NHTS(2017)			Sample		
	Gas price	Average MPG	Average VMT	Gas price	Average MPG[a]	Average VMT
	$/gallon ($2021)	miles/gallon	miles	$/gallon ($2021)	miles/gallon	miles
State						
Alaska	3.4	21.9	10,338	3.4	22.5	16,409
Alabama	2.3	23.9	13,246	2.3	24.9	12,737
Arkansas	2.3	22.7	12,101	2.3	24.3	12,466
Arizona	2.7	24.2	11,228	2.7	26.2	11,644
California	3.0	26.6	11,623	3.0	29.9	12,604
Colorado	2.2	23.9	11,886	2.2	24.9	11,274
Connecticut	2.6	25.0	11,342	2.6	29.2	11,359
District of Columbia	2.7	26.8	10,454	2.7	29.3	12,580
Delaware	2.6	23.8	12,686	2.6	28.3	13,761
Florida	2.4	24.6	11,479	2.4	25.7	12,299
Georgia	2.3	24.3	12,648	2.3	25.0	14,148
Hawaii	3.4	27.3	11,276	3.4	33.3	11,464
Iowa	2.4	23.3	11,510	2.4	24.6	11,725
Idaho	2.6	24.5	11,940	2.6	26.1	12,009
Illinois	2.5	24.1	12,115	2.5	24.6	12,414
Indiana	2.4	24.1	11,973	2.4	25.2	13,202
Kansas	2.4	23.1	12,392	2.4	26.3	11,412
Kentucky	2.4	24.3	13,433	2.4	27.1	15,447
Louisiana	2.3	22.5	12,269	2.3	24.4	9,569
Massachusetts	2.3	25.5	11,819	2.3	29.8	12,178
Maryland	2.6	25.1	12,700	2.6	25.8	13,331
Maine	2.6	24.3	12,643	2.6	24.6	13,618
Michigan	2.4	23.3	13,028	2.4	24.3	14,111
Minnesota	2.2	23.7	12,606	2.2	24.7	12,426
Missouri	2.3	24.0	12,458	2.3	23.5	13,262
Mississippi	2.3	22.6	14,206	2.3	22.8	18,960
Montana	2.6	23.1	11,964	2.6	23.8	12,394
North Carolina	2.5	24.1	12,520	2.5	24.7	13,485
North Dakota	2.5	20.9	11,811	2.5	23.7	15,182
Nebraska	2.5	23.2	11,333	2.5	25.8	11,077
New Hampshire	2.5	24.3	12,786	2.5	28.1	15,756
New Jersey	2.4	24.7	11,844	2.4	27.7	11,602
New Mexico	2.4	24.7	11,785	2.4	24.3	16,007
Nevada	2.8	25.0	10,689	2.8	25.6	10,353
New York	2.4	24.4	11,695	2.4	25.9	12,269
Ohio	2.3	24.5	12,433	2.3	24.9	13,835
Oklahoma	2.3	23.2	12,054	2.3	24.7	13,868
Oregon	2.9	25.8	10,750	2.9	25.7	10,553
Pennsylvania	2.6	24.0	11,461	2.6	24.9	12,553
Rhode Island	2.6	24.6	12,134	2.6	26.1	13,237
South Carolina	2.4	23.5	12,486	2.4	25.0	13,708
South Dakota	2.5	22.2	12,391	2.5	22.4	13,388
Tennessee	2.4	23.6	12,820	2.4	24.5	13,384
Texas	2.1	23.6	12,416	2.1	24.5	13,304
Utah	2.6	23.1	10,868	2.6	24.2	10,272
Virginia	2.4	25.4	11,548	2.4	27.8	12,625
Vermont	2.6	24.7	12,136	2.6	26.0	13,565
Washington	2.7	25.8	11,210	2.8	25.2	11,774
Wisconsin	2.5	23.7	12,511	2.5	24.7	13,433
West Virginia	2.6	24.4	12,047	2.6	23.3	13,578
Wyoming	2.4	21.7	12,941	2.4	24.4	17,878

Notes: Sources are described in the text. [a] The average MPG is the data after merging 2017 NHTS with Dataone.

TABLE 1.B.4. **Posterior Mean Parameter Estimates**

	Mean	St.Er.		Mean	St.Er.
Utility1			**Utility 1**		
Theta			**Theta**		
contant	-0.221	0.086	Chevrolet	-1.638	0.074
MSA 1	0.448	0.030	EU(BMW, Volkswagen, etc)	-1.734	0.051
MSA 2	-0.232	0.032	Ford	-0.385	0.030
MSA 3	0.629	0.030	Honda	-0.489	0.047
MSA 4	-0.018	0.032	Nissan	-1.236	0.030
MSA 5	-0.090	0.086	Toyota	-0.809	0.131
MSA 6	0.225	0.045	US (Jeep, Dodge,etc)	-1.518	0.039
MSA 7	-0.543	0.051	**Delta1**	0.064	0.059
MSA 8	-0.145	0.031	**Delta2**	-0.820	0.015
MSA 9	-0.457	0.030	**Mu**	0.864	0.386
MSA 10	-0.007	0.051			
MSA 11	0.221	0.066			
MSA 12	-0.083	0.029	**Utility 2**		
MSA 13	1.092	0.055	**Alpha**		
MSA 14	0.132	0.039	contant	-0.775	0.050
MSA 15	-0.076	0.049	workcount/numofcars	0.642	0.048
MSA 16	0.024	0.057	child	0.523	0.032
MSA 17	0.282	0.079	howner	-0.249	0.022
MSA 18	-0.035	0.039	subcost	0.693	0.049
MSA 19	-0.417	0.031	subvmt	0.318	0.046
MSA 20	-0.228	0.048	agem	-0.306	0.022
MSA 21	0.116	0.096	white	0.052	0.032
MSA 22	-0.447	0.031	college	-0.726	0.036
MSA 23	0.133	0.036	MSA size 1	0.249	0.051
MSA 24	0.112	0.048	MSA size 2	0.073	0.042
MSA 25	0.468	0.049	MSA size 3	-0.507	0.032
MSA 26	0.141	0.041	MSA size 4	-0.366	0.040
MSA 27	-0.212	0.047	MSA size 5	0.061	0.030
MSA 28	0.035	0.030	horsepower/weight	-0.043	0.029
MSA 29	-0.430	0.039	van	-0.763	0.088
MSA 30	0.643	0.050	SUV	0.000	0.031
MSA 31	0.238	0.089	Pick-up	0.007	0.054
MSA 32	0.439	0.047	ICE	-1.337	0.143
horsepower/weight	0.698	0.099	Hybrid	-1.270	0.125
van	-1.666	0.044	\$15,000<income<\$35,000	-0.417	0.053
SUV	0.702	0.038	\$35,000<income<\$50,000	-0.277	0.048
Pick-up	-0.823	0.078	\$50,000<income<\$75,000	-0.185	0.027
ICE	-2.412	0.114	\$75,000<income<\$125,000	0.012	0.033
Hybrid	-1.977	0.054	\$125,000<income	0.198	0.078
wheelbase	1.095	0.152	**lambda**	1.346	0.010
width	0.927	0.114	**sigma**	-1.602	0.017
height	0.840	0.092			

Notes: Variable definitions are in Table 1.B.5.

TABLE 1.B.5. **Definitions of Variables**

Variables	Description
MSA base	New England (ME, NH, VT, CT, MA, RI) MSA or CMSA of 1 million or more with heavy rail
MSA 1	New England (ME, NH, VT, CT, MA, RI) MSA or CMSA of 1 million or more without heavy rail
MSA 2	New England (ME, NH, VT, CT, MA, RI) MSA of less than 1 million
MSA 3	New England (ME, NH, VT, CT, MA, RI) Not in a MSA
MSA 4	Mid-Atlantic (NY, NJ, PA) MSA or CMSA of 1 million or more with heavy rail
MSA 5	Mid-Atlantic (NY, NJ, PA) MSA or CMSA of 1 million or more without heavy rail
MSA 6	Mid-Atlantic (NY, NJ, PA) MSA of less than 1 million
MSA 7	Mid-Atlantic (NY, NJ, PA) Not in a MSA
MSA 8	East North Central (IL, IN, MI, OH, WI) MSA or CMSA of 1 million or more with heavy rail
MSA 9	East North Central (IL, IN, MI, OH, WI) MSA or CMSA of 1 million or more without heavy rail
MSA 10	East North Central (IL, IN, MI, OH, WI) MSA of less than 1 million
MSA 11	East North Central (IL, IN, MI, OH, WI) Not in a MSA
MSA 12	West North Central (IA, KS, MO, MN, ND, NE, SD) MSA or CMSA of 1 million or more without heavy rail
MSA 13	West North Central (IA, KS, MO, MN, ND, NE, SD) MSA of less than 1 million
MSA 14	West North Central (IA, KS, MO, MN, ND, NE, SD) Not in a MSA
MSA 15	South Atlantic (DE, FL, GA, MD, NC, SC, WV, VA) MSA or CMSA of 1 million or more with heavy rail
MSA 16	South Atlantic (DE, FL, GA, MD, NC, SC, WV, VA) MSA or CMSA of 1 million or more without heavy rail
MSA 17	South Atlantic (DE, FL, GA, MD, NC, SC, WV, VA) MSA of less than 1 million
MSA 18	South Atlantic (DE, FL, GA, MD, NC, SC, WV, VA) Not in a MSA
MSA 19	East South Central (AL, KY, MS, TN) MSA or CMSA of 1 million or more without heavy rail
MSA 20	East South Central (AL, KY, MS, TN) MSA of less than 1 million
MSA 21	East South Central (AL, KY, MS, TN) Not in a MSA
MSA 22	West South Central (AR, LA, OK, TX) MSA or CMSA of 1 million or more with heavy rail
MSA 23	West South Central (AR, LA, OK, TX) MSA or CMSA of 1 million or more without heavy rail
MSA 24	West South Central (AR, LA, OK, TX) MSA of less than 1 million
MSA 25	West South Central (AR, LA, OK, TX) Not in a MSA
MSA 26	Mountain (AZ, CO, ID, MT, NM, NV, UT, WY) MSA or CMSA of 1 million or more without heavy rail
MSA 27	Mountain (AZ, CO, ID, MT, NM, NV, UT, WY) MSA of less than 1 million
MSA 28	Mountain (AZ, CO, ID, MT, NM, NV, UT, WY) Not in a MSA
MSA 29	Pacific (AK, CA, HI, OR, WA) MSA or CMSA of 1 million or more with heavy rail
MSA 30	Pacific (AK, CA, HI, OR, WA) MSA or CMSA of 1 million or more without heavy rail
MSA 31	Pacific (AK, CA, HI, OR, WA) MSA of less than 1 million
MSA 32	Pacific (AK, CA, HI, OR, WA) Not in a MSA
MSA size base	In an MSA of Less than 250,000
MSA size 1	In an MSA of 250,000 - 499,999
MSA size 2	In an MSA of 500,000 - 999,999
MSA size 3	In an MSA or CMSA of 1,000,000 - 2,999,999
MSA size 4	In an MSA or CMSA of 3 million or more
MSA size 5	Not in MSA or CMSA
subcost	The average operating cost of the other vehicles that the household owns
subVMT	The average VMT of the other vehicles that the household owns

Notes: The description of MSA is from the 2017 NHTS.

CHAPTER 2

A Vehicle Miles Traveled Tax to Reduce the Deficit as Electric Vehicle Grows

2.1. Introduction

In the past, the Highway Trust Fund for the federal surface transportation program was funded almost from the gasoline tax. However, the federal gasoline tax has been the same at 18.4 cents per gallon since 1993. Also, the gas tax is only on internal combustion engines (ICEs), while the number of electric vehicles (EVs) is increasing. The tax revenue is insufficient to cover the expenditure because of the unchanged gas tax rate, improved fuel economy, and increasing number of EVs. According to the Highway Trust Fund Accounts[1] in 2022, estimated revenues and interest are around $38 billion, but projected expenditure rises from $46 billion to $68 billion over the decade to 2030. The shortfall of the Highway Trust Fund is expected to expand from $4.7 billion in 2027 to $160.5 billion in 2032. The deficit grows by around $30 billion annually. To address this problem, Congress of the US has supported the federal surface transportation program by transferring the fund from the general fund of the Treasury to the Highway Trust Fund since 2008. The most recent intergovernmental transfers are bailouts of $10.4 billion in 2021 and $90 billion in 2022 in highway accounts. If it had not been for the recent transfers, it would have had a deficit in 2023. The high EV growth rate and constant gasoline tax will exacerbate the deficits.

There are three ways to address the continuously expanded deficit according to the Congressional Research Service[2]: ongoing transfer of general fund of the Treasury, fuel tax increase, and transition to VMT tax. Remitting additional funds through the internal government is not a fundamental solution and may result in a large deadweight loss. A gasoline tax hike cannot solve the cause of the

[1]https://www.cbo.gov/system/files/2022-05/51300-2022-05-highwaytrustfund.pdf
[2]https://sgp.fas.org/crs/misc/R45350.pdf

widespread use of electric vehicles in the long term. Hence, VMT tax would be the most efficient way to resolve the problem (Langer et al. (2017)).

This paper estimates gasoline and VMT tax rates reducing the discrepancy between revenue and expenditure as electric vehicle grows. This analysis aims to compare the consumer surplus under two policies and gauge the relative private benefit from the VMT tax to replace the federal gasoline tax in the case of a tax increase and expansion of electric vehicle distribution. Two alternative taxes to increase government revenue are estimated. One is to raise the gasoline tax without charging no tax on EVs. Another option is to increase the VMT tax, given the VMT tax that forces all vehicles on the road to drive at the same rate.

The counterfactual analysis is conducted in three cases: increasing the government revenue by 30%, the sensitivity analysis of the revenue increase from 30% to 100%, and the EV share increase from 3% to 10%. This paper takes the estimates from the two-period structural model of vehicle choice and utilization in Cheon (2022) for these analyses. It numerically finds gas and VMT taxes to increase the federal government revenue for each case. The counterfactual analysis of the two alternative policies compares the long-term impact of raising government revenues on consumer surplus. The long-term impact of the consumer surplus change is estimated by considering both changes in the vehicle composition and the utilization rate due to changes in taxes applied. The average length of car ownership is over six years[3]. Hence, total surplus is defined as the net consumer surplus for six years for each case. The first case of increasing the government revenue by 30% examines the moderate effect of raising the revenue. In addition, the following two sensitivity analyses examine the effects of a high growth rate of government revenue and a high proportion of electric vehicles. The first two analyses for the revenue increase are to compare the tax rate and tax type effects on the consumer surplus. The last analysis with different electric vehicle shares represents the effect of EV share on the surplus when the government raises the tax rate.

[3]https://www.cnbc.com/2017/05/28/car-owners-are-holding-their-vehicles-for-longer-which-is-both-good-and-bad.html

The baseline results suggest that consumer surplus loss from raising the VMT tax is slightly less than the gasoline tax. Given the long-term effect of new car ownership of six years, the net consumer surplus of VMT tax over gasoline tax is positive, albeit around \$3.0 per vehicle on average. In addition, it finds that the effects of the tax rate increase on consumer surplus differ depending on the fuel type. Under the gas tax increase, ICE holders are subject to higher taxes, resulting in a loss of utility for owning and driving a vehicle. However, EV owners have no effect of the gasoline tax increase on utilization, although there is a slight loss in the utility for vehicle choice.

Assuming government revenues double, the net consumer surplus of VMT tax compared to the gas tax is around \$10 per vehicle for six years, which is relatively small considering the period. However, it is worth noting that the VMT tax still gives a slight advantage over the gas tax on average. As the increasing rates in government revenue rise, the more VMT tax gives the net consumer surplus. Most of the benefits are from the utility of driving, not ownership. The incremental tax rates could be spread over all households, unlike the gasoline tax. The VMT tax is relatively more beneficial to households because it has a lower operating cost increase than the gas tax when increasing the revenue.

The last sensitivity analysis explores the effect of various EV shares in the market, from 3% to 10%, while maintaining the increase in government revenue for each tax. For a 30% increase in government revenue, the net consumer surplus of the VMT tax over the gasoline tax for six years is \$19.0 per vehicle when the EV share is 3% but expands to \$71.4 per vehicle when the EV share is 10%. Doubling government revenues increases the net surplus from \$31.2 to \$84.9 per vehicle for six years as the proportion of electric vehicles increases at the same rate. The welfare analysis concludes that tax rates affect consumer surplus more than tax types when increasing government revenues (Weatherford (2012)). However, as EV penetration increases, the role of tax types becomes important in the impacts of tax increases on consumer surplus.

Some literature compares gas and VMT taxes. Langer et al. (2017) suggests that a VMT tax is more efficient than a gas tax, especially when the government differentiates the tax rates with externalities. Weatherford (2012) find little differences in equity considerations between gasoline and VMT taxes. Metcalf et al. (2022) compares the distributional effects by income between the gas tax and VMT tax. Some literature studies about increasing tax rates. Bento et al. (2009) examines the distributional impacts of gas tax increase. Parry and Small (2005) suggests that the optimal gas tax rate is much higher than the current gas tax, which improves social welfare. This paper contributes to the literature by comparing surplus change between gas and VMT tax with considering the penetration of EV growth while increasing government revenues.

The rest of the paper is as follows. Section 2 briefly describes the econometric model. Section 3 provides the sources of data. Section 4 describes the estimation results. Section 5 illustrates the results of the counterfactual analysis. Section 6 concludes.

2.2. Description of the Empirical Model

This section lays out the two-period model in Cheon (2022) to estimate the effects of tax increases on vehicle choice and utilization decisions[4]. This model is developed with reference to Gillingham (2011) and Bento et al. (2009). The two-period structural model consists of two utility functions for each period. The utility function for the first period is the utility of owning a vehicle. In the first period, households assumed to be risk-neutral consumers consider the expected utility of driving in the second period when choosing a vehicle. The second-period utility is to determine the miles driven. In the second period, they decide the miles driven conditional on the vehicle purchased in the first period. The individual household optimizes the utilities for each vehicle independently.

The utility of the first period is a discrete choice model, and the error term follows the Type I extreme value as assumed in the prior studies. The specific functional form of the utility in the first

[4]A detailed description of this model can be found in Cheon (2022).

period is as follows:

$$
\begin{aligned}
U_{1,ijt}(E[U_{2,ijt}], z_{ij}^{\theta}, y_i, p_{ij}, r, d_i, M_{ijt}^{*}) &= \delta_{1,i} E[U_{2,ijt}] + \theta_{ij} + y_i - r p_{ij} + \delta_{2,i} p_{ij}^{R} + \epsilon_{ijt} \\
\theta_{ij} &= \tilde{\theta}_i z_{ij}^{\theta} \\
E[U_{2,ij}] &= \lambda_i(\frac{1}{2\alpha_{ij}} - E[c_{ij}] - \frac{\alpha_{ij}}{2}(E[c_{ij}]^2 + var[c_{ij}])) \\
p_{ij} &= (P_j^v - sub_{ij}) \\
p_{ij}^R &= (1 - d_j) P_j^v - \mu_i E[M_{ijt}^{*}]
\end{aligned} \tag{2.1}
$$

The utility in the first period depends on the expected utility of the household in the second period, household and vehicle characteristics, income, the opportunity cost of purchasing the vehicle, and the vehicle's expected resale price. The vector z_{ij}^{θ} contains the household region and vehicle characteristics. The household region is a dummy variable for 35 categories of MSA and public transportation[5]. The vehicle attributes include horsepower, vehicle types, fuel types, vehicle size(wheelbase, width, height), and brand(Chevrolet, Ford, Honda, Etc.). The opportunity cost of purchasing a vehicle is defined as the annual rental price based on the price of the vehicle purchased. Because alternative fuel vehicles are eligible to receive subsidies, the purchase price of vehicles varies widely depending on the vehicle and household. The households also consider the resale price for their vehicle chosen based on the depreciation rate by vehicle model and their mileage in the second period.

[5]The 2017 NHTS provides 35 household classes grouping by a combination of census division, MSA status, and presence of a subway system when a population greater than 1 million. The valid bins in the data set used in this analysis are 33 categories.

The second period's utility function determines the miles driven for the vehicle selected in the first period. The functional form of the utility in the second period is assumed as

(2.2)
$$
\begin{aligned}
U_{2,ij}(z_{ij}^{\alpha}, c_{ij}) &= \frac{1}{\alpha_{ij}}(M_{ij} - \frac{1}{2\lambda_i}M_{ij}^2) - c_{ij}M_{ij} \\
\alpha_{ij} &= -\tilde{\alpha}_i z_{ij}^{\alpha} \\
c_{ij} &= \begin{cases} (t_1 + g_i)(1/MPG_j) & \text{Gasoline tax (ICE)} \\ g_i(1/MPG_j) & \text{Gasoline tax (EV)} \\ t_2 + g_i(1/MPG_j) & \text{VMT tax} \end{cases}
\end{aligned}
$$

The operating costs, defined as the driving cost per mile driven by a vehicle, have a structural form to have the same unit, dollar per mile, regardless of vehicle fuel or tax type. It allows counterfactual analysis at different tax rates, tax types, and fuel types.

Households maximize utility by choosing the miles driven by the vehicle they own. From the utility function of the second period, the household chooses the miles driven as follows:

(2.3)
$$
\begin{aligned}
\tilde{M_{ij}} &= \underset{M_{ij}>0}{arg\,max}\, U_{2,ij}(z_{ij}^{\alpha}, c_{ij}) = \lambda_i - \alpha_i\lambda_i c_{ij} \\
M_{ijt}^{*} &= \tilde{M}_{ijt} + \eta_{ijt} \qquad\qquad \eta_{ijt} \sim N(0, \sigma_i^2)
\end{aligned}
$$

z_{ij}^{α} contains the household characteristics, vehicle attributes, and other vehicle attributes owned by the households. The household characteristics include the number of workers, working or retired status, having children or not, homeowner status, average adult age, race (white or not), education (above college or not), and six levels of population size of the Metropolitan Statistical Area (MSA), and six income groups. The vehicle properties include horsepower, vehicle type (car, van, SUV, and pickup truck), and fuel type (ICE, hybrid, and EV). It also includes the average operating cost and VMT of other vehicles owned by the household. η_{ijt} is a shock that is unknown in the first period but known in the second period and follows the normal distribution.

The optimized choices are repeated t times for each household, where t is the number of vehicles owned by the households. This model assumes an interior solution. All variables are defined as follows:

g_i: gasoline or electricity price excluding fuel tax for ICE or EV

t_1: gasoline tax

t_2: VMT tax

MPG_j: vehicle j's miles per gallon

c_{ij}: operating cost per mile

M_{ij}: vehicle miles traveled

z_{ij}^{α}: household and vehicle characteristics

z_{ij}^{θ}: households and vehicles characteristics

y_i: income

p_{ij}: vehicle j purchase price for household i

P_j^v: vehicle j price from the manufacturer

sub_{ij}: subsidy for i when purchasing a vehicle j

p_{ij}^R: expected future price of vehicle j for household i

r: interest rate

d_j: vehicle j depreciation rate

The remains are parameters that vary randomly across households.

Since the households consistently consider both utilities over the two periods, this model should be estimated simultaneously. Then, the parameters are estimated by maximizing the full likelihood function of two utility functions as follows.

$$
\begin{aligned}
L_i &= \Pi_{t=1}^{T_i}[\Pi_{j=1}^{J} Pr_{it}(j)^{1_{ijt}} \Pi_{j=1}^{J} l(M_{ijt}^{*}|j\ chosen)^{1_{ijt}}] \\
Pr_{it}(j) &= \frac{exp(U_{1,ijt})}{\Sigma_{k=1}^{J} exp(U_{1,ikt})} \qquad (2.4) \\
l(M_{ijt}^{*}|j\ chosen) &= \frac{1}{\sqrt{2\pi\sigma_i^2}} exp(-\frac{1}{2}(\frac{M_{ijt}-M_{ijt}^{*}}{\sigma_i})^2)
\end{aligned}
$$

2.3. Data

2.3.1. Data Sources. The primary dataset is the 2017 National Household Travel Survey (NHTS) of the US Department of Transportation. The rest of the data required for the model and analysis is from Energy Information Administration (EIA), the US Bureau of Labor Statistics (BLS), the US Market Database of Dataone, and the Highway Trust Fund (HTF) Account of Congressional Budget Office.

The 2017 NHTS contains demographic variables, including income, location of residence (MSA, urban or rural, states, and census division), family composition (having children or not), number of workers, and homeowner status. There are also several vehicle-related variables, such as the number of vehicles the households own, vehicle miles traveled, and other vehicle attributes in their garage. Brand, model, vintages, vehicle types (car, van, SUV, pickup truck), horsepower, fuel types (ICE, hybrid, EV), and MPG are also included. In this analysis, the conventional hybrid using gasoline fuel and having a non-rechargeable battery is classified into the same group as the internal combustion engine to simplify the analysis. This analysis only takes the vehicles produced during 2016-2017. This period has larger electric vehicle shares than including all datasets. It allows a sensitivity analysis of the growing share of EVs in the market and the effects of increasing taxes on ICE and EV holders separately.

The regional gasoline price and electricity rates are from EIA and BLS. I merge the gasoline price by the Core Based Statistical Area (CBSA) from BLS with the NHTS data set and the gasoline price by the states from EIA with the NHTS data set for the remaining region. It creates more diversity in the operating cost of the household. EIA's state electricity rates also have been merged with the NHTS data set to have the same period as the gas price.

Estimating the model requires more data than the dataset provided by the NHTS. Dataone provides vehicle attributes for each model, such as MPG/MPGe and MSRP (Manufacturer's suggested retail price). The conventional hybrid uses gas, but the plug-in hybrid can drive only on a battery using electric power. Hence, I take MPG for conventional hybrid fuel efficiency while MPGe for plug-in hybrid fuel efficiency. The MSRP for each model year is used as the vehicle retail price for all households. Vehicle purchase prices are calculated as the MSRP minus subsidies to obtain variety in price data over the households and estimate the amount consumers paid. State subsidy data is provided in the Alternative Fuels Data Center (AFDC) and each state's website.

CarEdge, a private company that provides vehicle information data to select a vehicle, provides the depreciation rates of vehicle models. Given that the average period of holding a new vehicle is around six-year, I use the five-year depreciation rate of each model-year vehicle to estimate the expected resale price.

HTF account announces the projections for the highway account and transit account. HTF account in May.2022 proposes that the highway account will turn into a deficit in 2027, even with the intragovernmental transfers of $90 billion in 2022. Based on this forecast, rates of tax increase are calculated to cover the discrepancy between government revenue and expenditures.

2.3.2. Description of the Sample Statistics. Table 2.1 summarizes the number of vehicles and the fraction of vehicles by vehicle type, income, and MSA size. It shows that vans and pickup trucks tend to have less MPG than cars. EVs only have car and SUV types in the period of analysis. The fraction of vehicles by MSA size indicates that populated areas prefer more efficient vehicles such as EVs or ICEs with high MPG. According to the data by income, regardless of vehicle efficiency, higher-income groups have more vehicles than the lower-income groups. For ICE, higher-income groups tend to own vehicles with lower MPGs than middle or low-income groups. However, most EV owners fall into the high-income group. Given that no EV buyers are in the lowest-income bracket, the high-income groups mainly seem to afford to purchase EVs.

Table 2.2 provides the household and vehicle characteristics by fuel type for the sample used in this analysis. Vehicle miles traveled seem to depend not only on the operating cost or fuel economy but also on other household or vehicle characteristics. EV owners' average income is explicitly higher than ICE owners. However, focusing on the ICEs, the average income of high-MPG-ICE holders is less than that of low-MPG-ICE holders. The proportion of more efficient vehicles in an urban area is more significant than in a rural area, regardless of fuel type. The group having children tends to have a lower MPG. That is because they prefer a van to a household with no child. The household working seems to purchase an EV more than the household retired.

Since this analysis takes new vehicle purchases, the average MPG tends to be higher than the average in the US. However, the distribution of each graph is quite similar to the distribution of all samples in 2017 NHTS. Figure 2.A.1 to 2.A.3 in Appendix 2.A show the household distribution for MPG, VMT, and operating cost of the vehicles in samples used in this analysis.

2.4. Estimation Results

This section reports the results of estimating the two-period model described in section 2.2. Estimation is performed with a Bayesian statistical approach using Gibbs sampling, one of the Markov chain Monte Carlo methods. It can estimate a large number of random parameters with less computational burden. The first 30,000 iterations are discarded as burn-in after 40,000 iterations. Then, every 10th iteration of the last 10,000 estimations is used to estimate the parameters, and every 200th iteration is taken to conduct the sensitivity analysis.

TABLE 2.1. **Vehicle Composition in the Data Sample**

	ICE		EV	Total
	Low MPG(13-25)	High MPG(25-49)	MPG(46-133)	
Counts of Vehicles				
Vehicle Types				
car	1,387	4,659	131	6,177
van	426	-	-	426
SUV	2,711	1,676	46	4,433
Pick-up	1,518	-	-	1,518
Income				
$0<income<$15,000	114	199	-	313
$15,000<income<$35,000	405	712	3	1,120
$35,000<income<$50,000	445	682	7	1,134
$50,000<income<$75,000	982	1,217	13	2,212
$75,000<income<$125,000	1,922	1,968	46	3,936
$125,000<income	2,174	1,557	108	3,839
MSA size				
MSA Less than 250k	956	925	12	1,893
MSA of 250k - 500k	589	638	23	1,250
MSA of 500k - 1,000k	821	918	14	1,753
MSA of 1,000k - 3,000k	896	1,061	27	1,984
MSA of 3 million or more	1,899	2,130	92	4,121
Not in MSA	881	663	9	1,553
Total	6,042	6,335	177	12,554
Fraction of Vehicles				
Vehicle Types				
car	0.23	0.74	0.74	0.49
van	0.07	0.00	0.00	0.03
SUV	0.45	0.26	0.26	0.35
Pick-up	0.25	0.00	0.00	0.12
Income				
$0<income<$15,000	0.02	0.03	0.00	0.02
$15,000<income<$35,000	0.07	0.11	0.02	0.09
$35,000<income<$50,000	0.07	0.11	0.04	0.09
$50,000<income<$75,000	0.16	0.19	0.07	0.18
$75,000<income<$125,000	0.32	0.31	0.26	0.31
$125,000<income	0.36	0.25	0.61	0.31
MSA size				
MSA Less than 250k	0.16	0.15	0.07	0.15
MSA of 250k - 500k	0.10	0.10	0.13	0.10
MSA of 500k - 1,000k	0.14	0.14	0.08	0.14
MSA of 1,000k - 3,000k	0.15	0.17	0.15	0.16
MSA of 3 million or more	0.31	0.34	0.52	0.33
Not in MSA	0.15	0.10	0.05	0.12
Total	1.00	1.00	1.00	1.00

Notes: Sources are described in the text. MPG used in this analysis is the data after merging 2017 NHTS with Dataone.

Table 2.2. **Household and Vehicle Characteristics by Fuel Types**

Variables	ICE Low MPG(13-25)	ICE High MPG(25-49)	EV MPG(46-133)	Total
Vehicle Miles Travel (Miles)	13,466	12,578	11,180	12,986
MPG	20.5	29.2	98.8	26.0
operating cost(cent, $2021)	12.2	8.7	6.3	10.3
Horsepower	288	180	218	233
Income ($2021)	138,733	112,215	199,108	126,203
Number of workers	1.13	1.14	1.27	1.14
average age among adults	53.8	53.6	51.9	53.6
Urban (%)	72.7	81.1	91.5	77.2
Rural (%)	27.3	18.9	8.5	22.8
Child (%)	24.4	17.9	27.7	21.1
No Child (%)	75.6	82.1	72.3	78.9
Work (%)	74.8	74.9	83.6	75.0
Retired (%)	25.2	25.1	16.4	25.0

Notes: Sources are described in the text. MPG used in this analysis is the data after merging 2017 NHTS with Dataone. The variables are weighted averages of all samples used in this analysis.

I take a couple of assumptions to estimate the model. First, households consider all vehicles produced in 2016-2017 for their choice set when maximizing their utility in the first period. In this paper, the households have a set of 362-year-model choices. This assumption ignores the outside option, such as using public transportation. However, as this paper aims to compare the effects of gas and VMT taxes, outside options would have little effect on the results. Also, households consider the opportunity cost of purchasing a vehicle in the first period. The average 10-year T-Bill for 2016-2017 is used to calculate opportunity costs. One could think that it is the rental price of the vehicle (Bento et al. (2009), Spiller (2012)). Lastly, it is assumed that households predict future gasoline prices based on current gas prices when expecting the utility of driving in the first period. This assumption lead to the assumption that the expected gasoline price is equal to the current gas price (Gillingham (2011), Anderson et al. (2013)). It allows for variability in future gas prices over households by region.

This section focuses on elasticities calculated with the estimates, which is more simply interpretable to read the results for the following analysis. The estimate results are in Table 2.A.1 in Appendix 2.A. Table 2.3 presents the three elasticities: the vehicle rental price of car ownership, operating cost elasticities of car ownership, and the operating cost elasticity of vehicle miles traveled. The table also shows whether these elasticities are heterogeneous over vehicle fuel types and household regions. The average car ownership elasticity with respect to the vehicle rental price for all households is -1.97, but the elasticity with respect to the operating cost is much smaller at around -0.01. It implies that households consider more about the vehicle price than the operating cost when purchasing a vehicle. In particular, EV owners are slightly more elastic to the vehicle price and slightly less elastic to the operating costs when purchasing a vehicle. The price of an electric car is much higher with similar specifications, which can prove to be much more critical when buying a vehicle. On the other hand, the average elasticities of census division are similar by region.

Conditional on the vehicles purchased in the first period, the VMT elasticity with respect to operating costs is -0.115. The elasticity of EVs is more significant than ICEs. It may be because households considering more operating costs when driving tend to purchase electric vehicles. The elasticity is heterogeneous over census regions. New England and West South Central have the lowest operating cost elasticity at around -0.09. Meanwhile, Mountain and Pacific have larger elasticities, -0.14 and -0.13, respectively, than other areas. It implies that the VMT elasticities depend not only on the operating cost but also on the geographic characteristics.

2.5. Counterfactual Analysis

This section examines the consumer surplus change over the long run in three cases: (1) the government tax revenue increased by 30%, (2) a sensitivity analysis that changes the rate of increase in government revenue from 30% to 100%, and (3) sensitivity analysis of various electric vehicle shares from 3% to 10% as government revenue increase. The first counterfactual analysis is a baseline scenario that provides a reference for comparing the outcomes of the following two scenarios. In all cases, I assume household preference is not changed by increasing tax rates or EV shares on the road. This assumption allows using the estimation results in section 2.4 for all analyses and resampling from the dataset for sensitivity analysis. In order to examine the long-term

TABLE 2.3. **Posterior Mean Elasticities with Average Estimates by Fuel Types and Region**

	Car ownership elasticity wrt rental price	Car ownership elasticity wrt operating cost	VMT elasticity wrt operating cost
All	-1.967	-0.009	-0.115
by vehicles			
Non-EV	-1.957	-0.009	-0.108
EV	-2.096	-0.005	-0.771
by region (Census division)			
New Egnland	-1.967	-0.009	-0.089
Middle Atlantic	-1.967	-0.009	-0.110
East North Central	-1.967	-0.008	-0.123
West North Central	-1.966	-0.008	-0.113
South Atlantic	-1.967	-0.008	-0.115
East South Central	-1.967	-0.008	-0.114
West South Central	-1.967	-0.008	-0.089
Mountain	-1.967	-0.009	-0.144
Pacific	-1.967	-0.010	-0.131

effects of increasing government revenue, the consumer surplus change is calculated using two components. One is the vehicle choice margins in the first period; the other is from the utility of driving in the second period, conditional on the vehicle choice. Small and Rosen (1981) proposes a method for calculating the welfare applicable for a Type I extreme value error in a discrete choice model. The consumer surplus change in the first period is calculated as follows:

$$\Delta E[CS_1] = \sum_i (log \sum_j exp(E[U_{1,ij}(c_1)]) - log \sum_j exp(E[U_{1,ij}(c_0)])) \tag{2.5}$$

where c_0 is the original operating costs per mile, and c_1 is the counterfactual operating cost before the policy change. For example, c_0 is the operating cost before the tax increase, and c_1 is the operating cost after the tax increase. I suppress other variables which are the same before and after the tax increase to simplify the notation. In addition, the consumer surplus change in the second period conditional on the chosen vehicle is calculated as follows:

$$\Delta E[CS_2] = \sum_{ij} E[U_{2,ij}(c_1)] - E[U_{2,ij}(c_0)] \tag{2.6}$$

The sum of consumer surplus change over the two periods is the total expected consumer surplus change in the long run. However, the first-period consumer surplus change occurs once the household purchases a vehicle. In the second period, consumer surplus change repeatedly occurs while maintaining the vehicle. I use the average 10-year T-Bills in 2016-2017 as a discount rate and calculate the present value of the consumer surplus change the following year after vehicle purchases. Unless otherwise specified, consumer surplus in the following sections represents the average surplus per vehicle.

2.5.1. Increasing Government Revenue. The federal government has considered adopting a VMT tax. Additionally, the 2022 Congressional Budget Office (CBO) Highway Trust Fund Account predicts that the highway trust fund will turn into a deficit of \$4.7 billion in 2027. Table 2.4 provides the projections of HTF deficits in highway accounts calculated at different government revenue growth rates without additional intergovernmental transfers. If the government raises the gasoline tax rate and collects an additional 20% of tax revenue, the discrepancy between revenue and expenditures is expected to turn positive in the first year. However, in the next year, it returns to a deficit. Even an increase in government revenues of up to 50% will not cover the deficit in the long run. Once the government reaps twice the revenue from a gasoline tax, the net balance sustains a similar level of positive value. The deficit forecasting suggests that double taxation could cover the expenditure. For the baseline counterfactual analysis, I consider a relatively modest increase in government revenue as 30% to compare the long-run impacts of the gasoline and VMT taxes on the consumer surplus as each tax increases the government revenue. After that, the following sensitivity analysis considers higher tax rates to increase government revenues.

Table 2.5 reports the tax rates to raise government revenue. The gas tax of 0.97 cents per gallon and the VMT tax of 24.0 cents per mile are required to obtain a 30% increase in revenue.

Table 2.4. **HTF Account Deficit Forecasting**

				($bn)
Increase Rate	**2027**	**2028**	**2029**	**2030**
0%	-4.7	-32.8	-62.7	-93.9
20%	1.5	-20.5	-44.2	-69.2
25%	3.1	-17.4	-39.5	-63.0
30%	4.6	-14.3	-34.9	-56.9
35%	6.1	-11.2	-30.3	-50.7
40%	7.7	-8.1	-25.7	-44.5
50%	10.8	-2.0	-16.4	-32.2
80%	20.1	16.6	11.4	4.8
100%	26.3	28.9	29.9	29.5

Notes: It is the author's calculations based on the projection of the Congressional Budget Office in May.2022.

Table 2.6 presents the consumer surplus change due to the VMT tax and gas tax to increase government revenue by 30%. The average net consumer surplus adopting the VMT tax with increasing government revenue is slightly positive at $0.4. The consumer surplus changes have two components: vehicle choice and driving margins. A 30% increase in government revenue reduces all consumer surplus under each tax policy compared to before the tax increase, regardless of tax type. The level of utility reduction for vehicle choice is similar regardless of tax type. When reaping more government revenue by 30% from VMT tax, the utility change in vehicle choice is -$25.4. The corresponding utility change under the gas tax is -$25.2. The reduction in the utility for vehicle choice across fuel economy is lowest for electric vehicles in both types of tax. It is because electric vehicles have lower ownership elasticity for operating costs than ICEs. However, the surplus change in the utility from driving has different impacts across the tax types, as the same tax rate increase affects operating costs differently. The average consumer surplus reduction is similar at $27.2 per vehicle per year for VMT tax and $27.8 per vehicle per year for the gas tax applied. However, the effects of the tax hike are heterogeneous over the fuel economy. To the extreme, EV holders are not affected by a gasoline tax increase in driving margins, but the VMT tax increase exacerbates the consumer surplus by -$25.7 per vehicle per year. The lower MPG vehicle holder relatively benefits from the VMT tax increase than the gas tax increase by around \$6.0 a year, whereas the higher MPG vehicle holder is worse off by \$3.9 a year.

TABLE 2.5. **VMT Tax and Gas Tax Required to Increase the Government Revenue**

Increasing Rates of Government Revenue	VMT tax		Gasoline tax		
	tax rate (cent/mile)	operating cost (cent/mile)	tax rate (cent/gallon)	operating cost (cent/mile)	Diff. in cost (cent/mile)
0%	0.74	10.32	18.4	10.34	-0.02
30%	0.97	10.55	24.0	10.57	-0.02
40%	1.05	10.62	25.8	10.65	-0.03
50%	1.12	10.70	27.7	10.73	-0.03
80%	1.35	10.92	33.3	10.96	-0.03
100%	1.50	11.08	37.1	11.12	-0.04

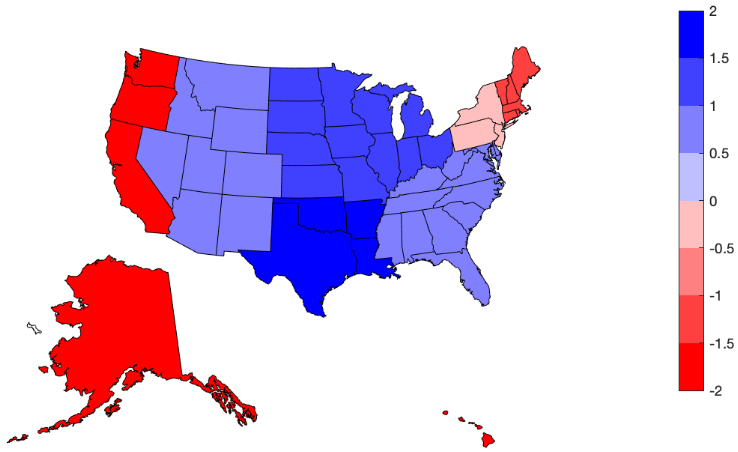
TABLE 2.6. **Consumer Surplus Change per Vehicle when Increasing Government Revenue by 30% ($/year)**

	VMT tax			GAS tax			Net CS		
	ownership	driving	Total	ownership	driving	Total	ownership	driving	Total
GR 30%	-25.4	-27.2	-52.6	-25.2	-27.8	-53.0	-0.2	0.6	0.4
Non-EV (Low MPG,13-25)	-24.2	-26.8	-50.9	-23.9	-32.8	-56.7	-0.2	6.0	5.8
Non-EV (High MPG,25-49)	-26.7	-27.6	-54.3	-26.5	-23.8	-50.2	-0.2	-3.9	-4.1
EV (MPG, 46-133)	-22.8	-25.7	-48.5	-22.6	0.0	-22.6	-0.2	-25.7	-26.0

TABLE 2.7. **Consumer Surplus Change per Vehicle: by vehicle ownership period when government revenue increases by 30% ($/year)**

	1 year	2 year	3 year	4 year	5 year	6 year	7 year	8 year
VMT tax								
GR 30%	-52.6	-79.2	-105.3	-130.9	-155.9	-180.4	-204.4	-228.0
Non-EV (Low MPG,13-25)	-50.9	-77.1	-102.8	-127.9	-152.6	-176.7	-200.4	-223.5
Non-EV (High MPG,25-49)	-54.3	-81.4	-107.9	-133.9	-159.3	-184.3	-208.7	-232.6
EV (MPG, 46-133)	-48.5	-73.7	-98.4	-122.5	-146.2	-169.4	-192.1	-214.4
Gas tax								
GR 30%	-53.0	-80.2	-106.8	-132.9	-158.4	-183.5	-208.0	-232.0
Non-EV (Low MPG,13-25)	-56.7	-88.8	-120.2	-151.0	-181.2	-210.7	-239.7	-268.0
Non-EV (High MPG,25-49)	-50.2	-73.5	-96.3	-118.7	-140.6	-162.0	-183.0	-203.6
EV (MPG, 46-133)	-22.6	-22.6	-22.6	-22.6	-22.6	-22.6	-22.6	-22.6
Net CS	0.4	0.9	1.5	2.0	2.5	3.1	3.6	4.1
Non-EV (Low MPG,13-25)	5.8	11.7	17.4	23.1	28.6	34.0	39.3	44.5
Non-EV (High MPG,25-49)	-4.1	-7.9	-11.6	-15.2	-18.8	-22.3	-25.7	-29.0
EV (MPG, 46-133)	-26.0	-51.1	-75.8	-100.0	-123.7	-146.8	-169.6	-191.8

FIGURE 2.1. Net Consumer Suplus Change of VMT Tax by Census when Government Revenue Increased by 30% ($/vehicle/year)



Notes: The net consumer surplus is the difference between the change in consumer surplus from the VMT tax and the change in consumer surplus from the gas tax. The change in consumer surplus for both tax policies is caused by raising the tax from the revenue-neutral tax rate to a rate that increases government revenue by 30%.

Figure 2.1 shows the net consumer surplus per vehicle a year of VMT tax over gas tax by census division when tax is applied to increase revenue by 30%. Pacific, New Egland, and Middle Atlantic tend to lose out under VMT tax. The more central the region, the greater the VMT tax benefit. Figure 2.2 and 2.3 show the average income and miles per gallon by the census division, respectively. These figures suggest that higher-income area suffers more from the VMT tax. The correlation between the net consumer surplus of VMT tax and MPG is more explicit than the correlation with income. The VMT tax incurs more losses than the gasoline tax in the region with higher vehicle fuel economy averages when the tax increases government revenues. The areas with more efficient vehicles, such as the West, suffer more.

FIGURE 2.2. Average Income by Census ($10k)

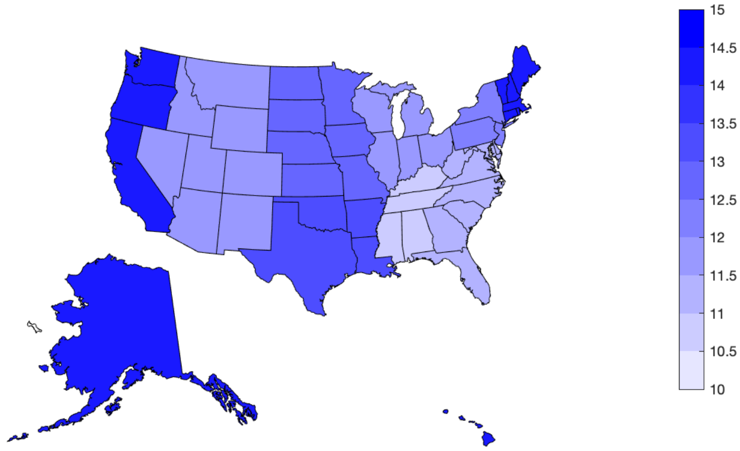


FIGURE 2.3. Average Miles Per Gallon by Census

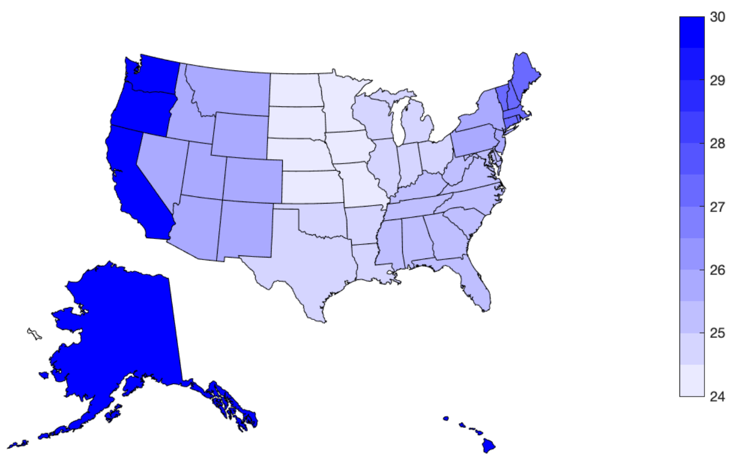


Table 2.7 presents consumer surplus change per vehicle throughout the vehicle ownership for a 30% increase in government revenue under each tax policy. The first-period utility for a vehicle

choice occurs once per vehicle, and the second-period decision to drive repeatedly occurs while holding the vehicle. When comparing the two tax types, the reduction in consumer surplus under the VMT tax increases less with vehicle tenure than the gasoline tax. I find that the net consumer surplus gain from a VMT tax versus the gas tax is around only $0.4 per vehicle for one year, but it is magnified up to $4.0 per vehicle over eight years. Although this change is small relative to the term, it is worth noting that the net consumer surplus of VMT tax is always positive from the first year of ownership to the term of ownership and increases as the holding period increases. The relative effects of the VMT tax on fuel economy when raising taxes are even more apparent. Across the fuel efficiency, only low-MPG vehicle holders relatively benefit from VMT tax, which covers the net loss on vehicles with high-MPG vehicles and EVs, making the average positive.

According to most surveys, the average car ownership period is six years or more. Hence, the following sensitivity analysis defines the total net surplus as the net consumer surplus change for six years.

2.5.2. Sensitivity Analysis of Government Revenue Growth Rate. A 30% increase in government revenue reduces the deficit but does not sufficiently cover spending. The government may need to double the tax to make up for the deficit with the gasoline tax. Therefore, it is interesting to examine the effect of the taxes that increase revenues from gas and VMT taxes by up to a factor of two. This section performs sensitivity analysis for various increases in government revenue and compares changes in consumer surplus due to VMT and gas tax increases.

Table 2.5 illustrates the tax rates required to increase government revenue from 30% to 100% and the corresponding operating cost per mile. The original VMT and gas tax rates are 0.74 cents per mile and 18.4 cents per gallon, respectively. The gas tax is the current federal gasoline tax. The VMT tax is at the level of sustaining the same government revenue as the gas tax (Cheon (2022)). To double the revenue, the government should raise taxes more than double, regardless of the tax type, because higher operating costs result in less driving. Hence, the VMT and gasoline tax to collect twice the revenue are estimated at 1.50 cents per mile and 37.1 cents per gallon, respectively.

TABLE 2.8. **Consumer Surplus Change per Vehicle: by different rates of government revenue increase ($/year)**

	VMT tax			GAS tax			Net CS		
	ownership	driving	Total	ownership	driving	Total[a]	ownership	driving	Total[a]
GR 30%	-25.4	-27.2	-180.4	-25.2	-27.8	-183.5	-0.2	0.6	3.1
GR 40%	-33.9	-36.3	-240.7	-33.6	-37.0	-244.8	-0.3	0.8	4.1
GR 50%	-42.4	-45.3	-301.0	-42.1	-46.3	-306.2	-0.3	1.0	5.2
GR 80%	-68.1	-72.7	-482.3	-67.5	-74.2	-490.5	-0.6	1.5	8.2
GR 100%	-85.2	-90.9	-603.5	-84.5	-92.8	-613.9	-0.7	1.9	10.3

Notes: Total surplus change is the value per vehicle in the case that the vehicle is held for 6 years.

In other words, the average operating cost under VMT tax increases from 10.32 cents per mile to 11.08 cents per mile, while the cost under gas tax increases from 10.34 cents per mile to 11.12 cents per mile. The operating cost under the VMT tax is relatively lower than the gas tax. Also, it shows that the difference in operating costs between the two taxes gradually widens as the government tax revenue increases.

Table 2.8 summarizes the results of consumer surplus change for each tax rate. The higher the tax rates, the more consumer surplus decreases in both taxes. However, it affects the utility of the two periods differently. The average consumer surplus under the gas tax in the first period decreases slightly less than the VMT tax for all augmented rates because the gasoline tax increases have a heterogeneous effect on the utility of purchasing a vehicle. As the VMT tax rate rises, the utility of purchasing a car decreases evenly on the vehicle choice margin. On the other hand, the higher the gasoline tax rate, the lower the operating cost increases and the higher the probability of purchasing a vehicle with a high-MPG vehicle (Linn (2016), Hymel and Small (2015)). Then, the average consumer surplus change per household from the gas tax increase is less than the VMT tax.

Meanwhile, the consumer surplus changes on vehicle driving margin find that the losses from VMT taxes are slightly less than gas taxes. It is because households with fuel-inefficient vehicles have lower VMT elasticity and drive more than those with EVs or high-MPG vehicles(Langer et al. (2017)). The heterogeneous gas tax effects on operating costs increase the operating costs of vehicles with lower MPG than others. As their consumer surplus changes worsen in driving margin, they further reduce the total average surplus under the gasoline tax.

Additionally, the results report that the consumer surplus loss for six-year is magnified roughly from \$180 to \$600 under both tax types when the revenue increase rates rise from 30% to 100%. The differences in losses between VMT tax and gas tax are pretty slight, considering the six years. However, the net consumer surplus of VMT tax versus gas tax augments from \$3 to \$10 for the same period. It is consistent results with the counterfactual analysis in section 2.5.1, suggesting that the VMT tax provides some advantages over a gasoline tax when raising the tax rates.

2.5.3. Sensitivity Analysis of Different Electric Vehicle Shares. The share of electric vehicles is a critical component in determining the tax level. According to Davis and Sallee (2020), a 1% EV share of all registered vehicles would reduce the gas tax revenue by \$250 million per year. This section conducts a sensitivity analysis using various electric vehicle shares ranging from 3% to 10% when increasing government revenues from 30% to 100%. This section proposes the apparent effect of the VMT tax over the gasoline tax when electric vehicle penetration expands while government revenues increase.

Table 2.9 suggests the tax rates required to increase revenue by 30% with different EV market shares and the operating costs per mile for each tax policy. When the proportion of electric vehicles rises to 10%, the gasoline tax rate should also rise at a similar rate to sustain the government revenue. However, the VMT tax rate is constant regardless of the proportion of electric vehicles. Operating costs subject to VMT tax are around 10.55 cents per mile in all cases of EV shares. However, under the gas tax policy, the operating costs gradually increase from 10.57 cents/gal to 10.68 cents/gal, resulting in higher costs than the VMT tax. Therefore, the consumer surplus under the VMT tax is consistent regardless of the EV portion. However, as EV share increases, the required incremental gasoline tax reduces consumer surplus much more than the VMT tax.

Table 2.10 reports the consumer surplus changes with different assumptions for the EV share when government revenues increase by 30%. As the assumption, even if the number of electric vehicles on the road increases, households' preference does not change. Since electric vehicles range less than non-electric vehicles, the government may have to increase the taxes slightly when they want to reap the same revenue as the EVs grow. Hence, when the VMT tax is imposed, as the EV shares increase from 3% to 10%, the utility reduction is expanded slightly from -$1.7 to -$6.3 per vehicle for six years[6]. A gasoline tax increase, on the other hand, reduces utility much more than a VMT tax as EV share increases. Thus, the net consumer surplus of VMT tax over gas tax is $19.0 for six years at 3% EV share and expands to $71.4 per vehicle at 10% EV share. Considering the US's 280 million vehicles on the road, the total net consumer surplus change for six years is roughly $20 billion.

[6]If the miles driven by EV approach the miles driven by ICE, the constant VMT tax would not result in a reduction in utility.

TABLE 2.9. **VMT Tax and Gasoilne Tax Required to Increase Government Revenue by 30% under Different EV Shares**

EV sharein Market	VMT tax tax rate (cent/mile)	VMT tax operating cost (cent/mile)	Gasoline tax tax rate (cent/gallon)	Gasoline tax operating cost (cent/mile)	Diff. in cost (cent/mile)
1%	0.97	10.55	24.0	10.57	-0.02
3%	0.97	10.55	24.6	10.60	-0.05
5%	0.97	10.55	25.1	10.62	-0.07
7%	0.98	10.55	25.7	10.64	-0.09
10%	0.98	10.55	26.6	10.68	-0.12

TABLE 2.10. **Consumer Surplus Change per Vehicle: by different EV Shares when government revenue increases by 30% ($/year)**

	VMT tax			GAS tax			Net CS		
	ownership	driving	Total	ownership	driving	Total[a]	ownership	driving	Total[a]
EV 3%	-0.2	-0.3	-1.7	-2.9	-3.1	-20.7	2.7	2.9	19.0
EV 5%	-0.4	-0.5	-3.0	-5.3	-5.6	-37.0	4.8	5.1	34.1
EV 7%	-0.6	-0.7	-4.3	-7.7	-8.1	-53.7	7.1	7.4	49.4
EV 10%	-0.9	-1.0	-6.3	-11.5	-11.6	-77.8	10.7	10.7	71.4

Notes: Total surplus change is the value per vehicle in the case that the vehicle is held for 6 years.

Figure 2.4 shows the effect of EV share and government increase on net consumer surplus of VMT taxes. As mentioned above, the increase in VMT tax compared to the gas tax leads to a positive change in consumer surplus due to the low VMT elasticity of fuel-inefficient vehicles. A higher revenue growth rate progressively increases the net consumer surplus of VMT tax over gas tax. In addition, when the proportion of electric vehicles increases, it contributes to the net surplus by distributing the tax burden to electric vehicle owners. The assumption for EV share from 3% to 10% augments the net surplus of VMT tax relatively steeply. Also, as government revenues increase, net consumer surplus from the introduction of the VMT tax increases as electric vehicles grow. It implies that, in the long run, the penetration rate of electric vehicles is the primary pathway that determines the tax rate to obtain a certain amount of government revenue and influences consumer surplus.

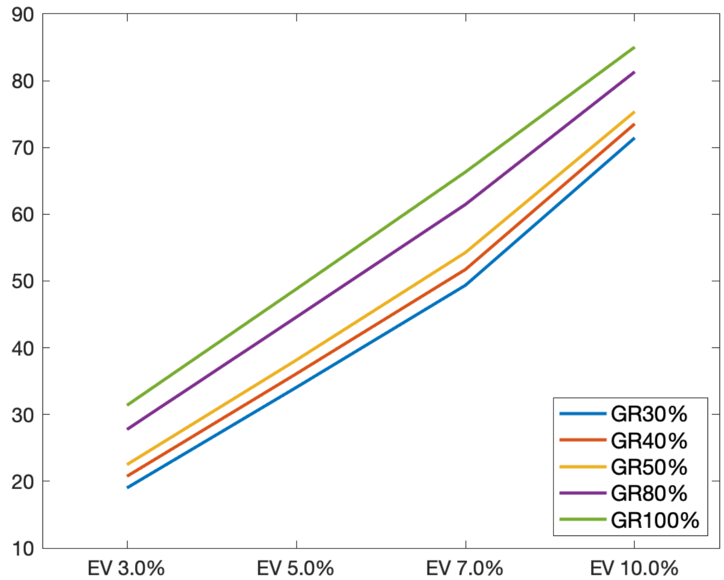
2.6. Conclusion

This paper contributes to the empirical literature for examining the effectiveness of the VMT tax by considering increasing the government revenue and electric vehicle market share. The main goal of this paper is to compare the long-term consumer surplus effects of gasoline and VMT tax increases along with the expectation for electric vehicle growth.

The consumer surpluses under both taxes are compared in three scenarios. One is increasing government revenue by 30% with two taxes, gas and VMT tax. I also conduct two sensitivity analyses in which government revenue and EV shares in the market increased at different rates. Given the growing interest in the policy shift toward the VMT tax and the growing market share of EVs, this analysis is timely and essential.

The results of the welfare analysis have several conclusions. First, a VMT tax leads to a slightly positive consumer surplus compared to a gas tax when it increases government revenue regardless of the rate of increase. The comparative gains of the VMT tax over gas tax are pronounced in regions with lower fuel economy vehicles than in regions with higher fuel economy. Second, consumer surplus is affected more by the tax rate rather than the tax type when it increases government

FIGURE 2.4. The Net Consumer Surplus Change per Vehicle for 6 years of VMT Tax when Different Government Revenue Increase Rates and Electric Vehicle Shares ($/vehicle)



Notes: The net consumer surplus is the difference between the change in consumer surplus from the VMT tax and the change in consumer surplus from the gas tax. The change in consumer surplus for both tax policies is caused by raising the tax from the revenue-neutral tax rate to a rate that increases government revenue with different EV shares. The surplus value is estimated by assuming that the vehicle is held for six years.

revenue. The VMT tax has a slightly smaller loss when it raises the revenues, but both the gas tax and the VMT tax produce a similar amount of loss in consumer surplus when they increase government revenues at the same rate. A final implication is that tax types become influential in changing consumer surplus as the share of electric vehicles increases. Higher EV shares require higher gasoline taxes even to maintain the same growth rate of government revenue. However, the VMT tax is consistent over different EV shares. Therefore, the net consumer surplus of VMT tax over gas tax is increasing as EV penetration augments.

This work could be extended to several future studies. One interesting study is to consider various policy objectives of governments instead of increasing tax revenue. One could imagine a policy goal to reduce gasoline consumption or mileage. Another avenue for further research is to make assumptions about the miles EVs travel as the EV market grows. As the EV market share rises, the average mileage of EVs may increase. California, one of the largest EV markets in the US, is targeting 5 million Zero Emissions Vehicles on the roads by 2030 and 250,000 EV charging stations by 2025. This electric vehicle support policy allows EV owners to drive more than before. As the distance traveled by EV increases, the net VMT tax benefit would be more significant than this analysis results. Finally, states could conduct similar studies to guide policymakers toward transitioning to VMT taxes in their states.

Appendix

2.A. Data and Estimate Results

2.A.1. Data Sample. Figure 2.A.1 to 2.A.3 illustrate the household distribution for MPG, VMT, and operating cost of the vehicles in samples used in this analysis. Even though this analysis takes only new vehicle purchases for 2016-2017, the distribution of each graph is quite similar to the distribution of all samples in 2017 NHTS. It suggests that the sample could represent the whole sample appropriately.

2.A.2. Estimate Results. This paper uses the same model and data, so the estimation results for all parameters are the same as the results in Cheon (2022). Table 2.A.1 summarizes the posterior mean and standard error of each random parameter coefficient. Most signs of the coefficients are as expected. For example, the coefficient of expected utility for the second period in the first-period utility function is small but positive. In estimates for the second period, the average coefficients of having children and working are positive, indicating that they tend to drive more than the other groups without children or in retirement.

FIGURE 2.A.1. Miles Per Gallon by Vehicles in the US (Samples used in this analysis)

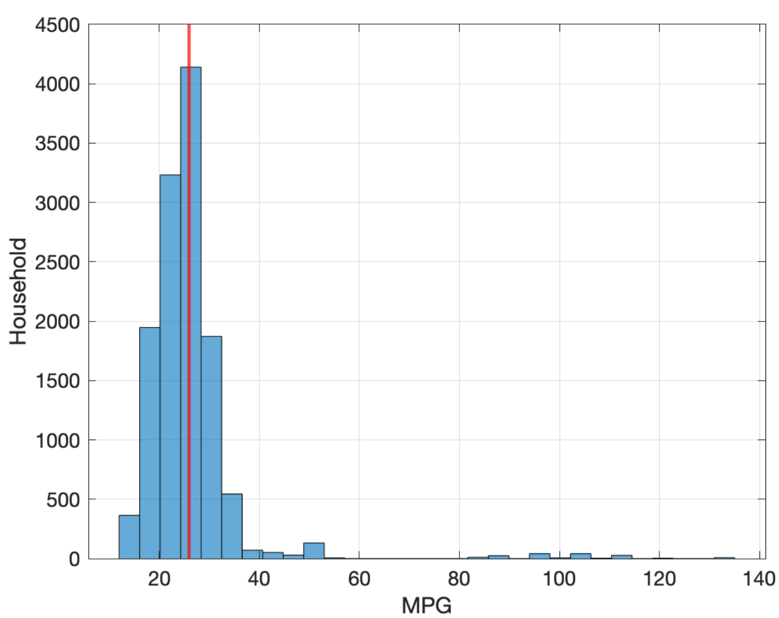


FIGURE 2.A.2. Vehicle Miles Traveled by Vehicles in the US (Samples used in this analysis)

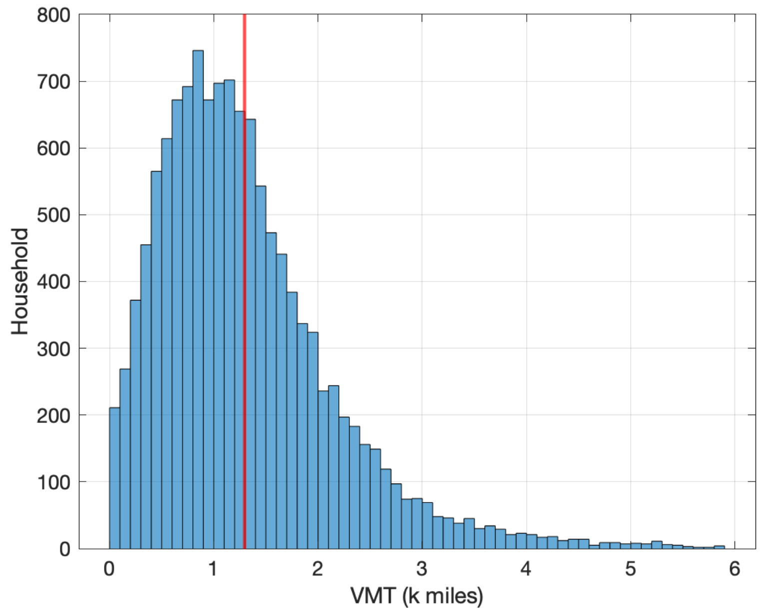


FIGURE 2.A.3. Operating Cost for Driving by vehicles in the US (Samples used in this analysis)

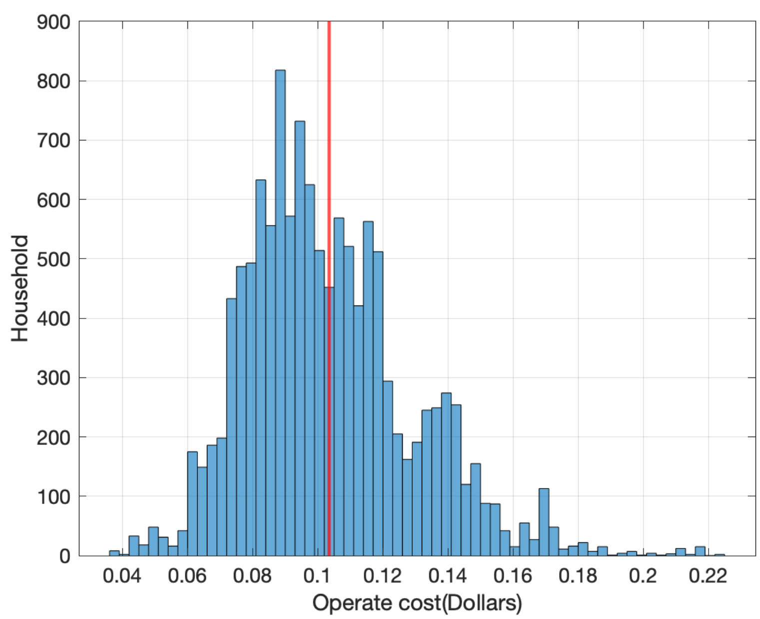


Table 2.A.1. **Posterior Mean Parameter Estimates**

	Mean	St.Er.		Mean	St.Er.
Utility1			**Utility 1**		
Theta			**Theta**		
contant	-0.221	0.086	Chevrolet	-1.638	0.074
MSA 1	0.448	0.030	EU(BMW, Volkswagen, etc)	-1.734	0.051
MSA 2	-0.232	0.032	Ford	-0.385	0.030
MSA 3	0.629	0.030	Honda	-0.489	0.047
MSA 4	-0.018	0.032	Nissan	-1.236	0.030
MSA 5	-0.090	0.086	Toyota	-0.809	0.131
MSA 6	0.225	0.045	US (Jeep, Dodge,etc)	-1.518	0.039
MSA 7	-0.543	0.051	**Delta1**	0.064	0.059
MSA 8	-0.145	0.031	**Delta2**	-0.820	0.015
MSA 9	-0.457	0.030	**Mu**	0.864	0.386
MSA 10	-0.007	0.051			
MSA 11	0.221	0.066			
MSA 12	-0.083	0.029	**Utility 2**		
MSA 13	1.092	0.055	**Alpha**		
MSA 14	0.132	0.039	contant	-0.775	0.050
MSA 15	-0.076	0.049	workcount/numofcars	0.642	0.048
MSA 16	0.024	0.057	child	0.523	0.032
MSA 17	0.282	0.079	howner	-0.249	0.022
MSA 18	-0.035	0.039	subcost	0.693	0.049
MSA 19	-0.417	0.031	subvmt	0.318	0.046
MSA 20	-0.228	0.048	agem	-0.306	0.022
MSA 21	0.116	0.096	white	0.052	0.032
MSA 22	-0.447	0.031	college	-0.726	0.036
MSA 23	0.133	0.036	MSA size 1	0.249	0.051
MSA 24	0.112	0.048	MSA size 2	0.073	0.042
MSA 25	0.468	0.049	MSA size 3	-0.507	0.032
MSA 26	0.141	0.041	MSA size 4	-0.366	0.040
MSA 27	-0.212	0.047	MSA size 5	0.061	0.030
MSA 28	0.035	0.030	horsepower/weight	-0.043	0.029
MSA 29	-0.430	0.039	van	-0.763	0.088
MSA 30	0.643	0.050	SUV	0.000	0.031
MSA 31	0.238	0.089	Pick-up	0.007	0.054
MSA 32	0.439	0.047	ICE	-1.337	0.143
horsepower/weight	0.698	0.099	Hybrid	-1.270	0.125
van	-1.666	0.044	\$15,000<income<\$35,000	-0.417	0.053
SUV	0.702	0.038	\$35,000<income<\$50,000	-0.277	0.048
Pick-up	-0.823	0.078	\$50,000<income<\$75,000	-0.185	0.027
ICE	-2.412	0.114	\$75,000<income<\$125,000	0.012	0.033
Hybrid	-1.977	0.054	\$125,000<income	0.198	0.078
wheelbase	1.095	0.152	**lambda**	1.346	0.010
width	0.927	0.114	**sigma**	-1.602	0.017
height	0.840	0.092			

Notes: This estimate result is from Cheon (2022).

CHAPTER 3

Could Gas Tax Combined with VMT Tax Be Effective During the Transition?

3.1. Introduction

The negative externalities of transportation include air pollution, accidents, and congestion. Some (e.g., climate change) are highly correlated with gasoline consumption, while others (e.g., local air pollution, accidents, congestion) are highly correlated with driving miles traveled. The gasoline or vehicle miles traveled (VMT) tax reduces the problem by taxing gasoline consumption or miles traveled. However, a gasoline tax cannot internalize the externalities of driving non-internal combustion engines such as electric vehicles. The efficiency of a gasoline tax could decrease as alternative fuel vehicles increase. Some states in the US have pilot programs in place. However, most literature (Goldstein (2014), Coyle et al. (2011)) stresses that replacing a gasoline tax with a VMT tax is challenging, even though the VMT tax more directly addresses some of the externalities and steadily raises the revenue regardless of the fuel economy improvements. Therefore, it is interesting to consider whether we can improve social welfare by having two types of tax, gas and VMT tax, simultaneously during the policy transition from a gas tax to a VMT tax.

This paper compares the efficiency of relying solely on a gasoline tax with two alternative policy options: (1) relying only on an optimal VMT tax or (2) optimally combining a VMT tax with a gas tax. It suggests the second-best optimal tax rate for each type to compare social welfare. The second-best optimal tax means the tax rate derived from the model to maximize the welfare given the tax types. Additionally, it discusses revenue-neutral taxes of the corresponding tax types. This paper develops the analytic frameworks to estimate the second-best optimal gas tax, VMT taxes, and combined taxes. First, it suggests the second-best optimal rates of flat taxes, such as a gas tax, a flat VMT tax, and a flat VMT+gas tax. A flat VMT tax is to levy a VMT tax equally on internal combustion engines (ICEs) and electric vehicles (EVs). A flat VMT+gas tax is a combined tax in which a flat VMT tax is added to a gas tax. Also, two differential tax types are defined as extensions: differential VMT tax and EV VMT+gas tax. The differential VMT tax refers to the different VMT tax rates applied to ICE and EV. For the EV VMT+gas tax, ICE is subject to the gas tax, and EV is subject to the VMT tax.

The model has some similarities with Parry and Small (2005) to describe the externality, but there are two notable differences from the literature. One is that the model presumes EVs are involved in a different market that shares externalities with ICEs. The model separately establishes the two respective markets of ICEs and EVs. The vehicles of the two markets can be substituted for each other, but the fuel cannot be substituted. Therefore, it assumes that the tax in one market does not affect the fuel consumption or miles driven in the other market. However, both markets are affected by total pollution, accidents, and congestion externalities in two markets. The externalities like congestion and accidents are assumed not to differ with the vehicle fuel types[1]. However, fuel efficiency, pollution cost, fuel price, and fuel consumption differ between ICEs and EVs. The other distinction is that this paper gauges the welfare effect by combining the gas and VMT taxes. It reveals the welfare change from introducing a VMT tax while sustaining the gas tax policy. The tax rates proposed in the framework are derived from normative analysis and estimated numerically using observational data for parameter values assumed to be socially optimal.

The frameworks first provide the formulas of the second-best optimal gasoline tax, flat VMT tax, and flat VMT+gas tax on the two types of vehicles - ICEs and EVs. It finds that the flat VMT tax and flat VMT+gas tax, converted in cents per gallon, are higher than the gas tax at the second-best optimal level. These taxes entail as much marginal external cost as the tax can address in each market. Imposing a gas tax adjusts the consumers' behavior by selecting more efficient vehicles, which leads the tax only to impact miles driven indirectly. It limits the effectiveness of gas taxes

[1]The accident costs as negative externality is defined as uncompensated cost by drivers. There is no clear evidence about the accident cost comparison between ICEs and EVs. Hence, this paper assumes the external cost is the same.

in correcting market failures. On the other hand, most of the externalities are related to mileage rather than fuel consumption. Because the VMT tax directly affects mileage, it compensates for externalities more efficiently than the gas tax and should therefore be set at a higher tax rate (Parry and Small (2005)). It leads to a higher VMT tax for ICEs than the gas tax at the second-best optimal tax rate. Also, the literature (Tong and Azevedo (2020)) indicates that the difference in externality cost in the two markets is insignificant. Therefore, the flat VMT tax, a value of the weighted sum of the marginal external costs in each ICE and EV market, is also higher than the gas tax. Similarly, the flat VMT+gas tax is higher than the gas tax at the second-best optimal tax. The higher tax rates address the more external costs.

The social welfare of the flat VMT+gas tax is close but slightly higher than the flat VMT tax at the second-best optimal level. The second-best optimal flat VMT+gas tax optimally combines a gas tax and VMT tax to maximize the welfare gain. By the construction, if the gas tax has already been set, the flat VMT+gas tax reaps the marginal benefits at the beginning of charging the gas tax and then gains additional marginal benefits from imposing the flat VMT tax. Generally, the VMT demand elasticity is less than the fuel price elasticity. The literature (Parry and Small (2005)) suggests that the VMT demand elasticity ratio of the fuel demand elasticity is less than 0.5. It implies that the initial marginal benefit of introducing a gas tax is greater than that of a VMT tax. Still, the difference reverses as the tax increases, reflecting the efficiency of the VMT tax. Therefore, the flat VMT+gas tax rate raises similar government revenues as the flat VMT tax, resulting in a similar tax burden but providing higher social welfare than the flat VMT tax.

Besides the second-best optimal tax, this paper discusses the best revenue-neutral tax of the proposed various tax types. The results suggest that the combined tax type dominates unless EVs are the predominant vehicle type on the road. Of the proposed tax types, only the flat VMT+gas tax as the best revenue-neutral tax is advantageous when few EVs are on the market. The flat VMT+gas tax numerically sets the gas tax and VMT tax rates at the rate that can obtain the greatest welfare benefits. It only requires a low VMT tax with a high portion of a gas tax. The welfare benefits of the VMT tax, capped with the current government revenue, do not offset the losses of eliminating the current gas tax. However, if electric vehicles continue to grow, all tax types except the gas tax will improve social welfare significantly. That is because even if the VMT tax rate is low, a sufficiently large share of electric vehicles allows welfare gains of the VMT tax can offset the loss caused by the abolition of the gas tax. The flat VMT+gas tax is more beneficial than the flat VMT tax until the EV share reaches 40%. After all, the EV VMT+gas tax benefit is the largest, followed by the differential VMT tax, while the flat VMT and flat VMT+gas tax have similarly a significant welfare gain.

There is a couple of literature discussing the optimal gasoline tax. The notable paper about the optimal gas tax is Parry and Small (2005). They develop an analytical framework to calculate the optimal gasoline tax for the US and UK, considering pollution, congestion, accident externalities, and income tax related to the Ramsey tax component. Lin and Prince (2009) adds the cost of oil dependence to the same framework in Parry and Small (2005) to obtain the optimal gasoline tax for California. Both papers present that the optimal gasoline tax is higher than the current tax in the US or California. Davis and Sallee (2020) give salience to EV's market effects on government revenue. They find out that EVs reduced annual tax revenues by $250 million in 2017. Bjertnæs (2019) studies the combination of taxes on fuel and vehicle fuel economy. Meanwhile, this is the first study on the theoretical optimal tax combining a gasoline and VMT tax in explicit consideration of the electric vehicle market.

The rest of the paper is organized as follows. Section 2 describes the theoretical model to find the second-best optimal taxes given tax types. Section 3 presents the data sources and parameters applied in the model. Sections 4 and 5 explore the empirical results and the welfare effects of the taxes discussed, respectively. Section 6 discusses the best revenue-neutral tax rates and their welfare change. The last part concludes.

3.2. Theoretical Model

3.2.1. Analytical Framework. The representative agent in a static and closed economy model has the following utility function.

$$U_k = u(C_k, M_k, T_k, H_k, S) - \varphi(P) - \delta(A) \tag{3.1}$$

C, M, T, H, and S are a numeraire consumption good, vehicle miles traveled, time to drive, vehicle characteristics, and government spending for insufficient infrastructure related to transportation, respectively. To simplify the model, the government spends the revenue on EV infrastructure. One can consider that S is the policy support for EVs[2]. The subscript k consists of two types of vehicle, $k \in \{1, 2\}$, meaning 1 is an internal combustion engine (ICE) and 2 is an electric vehicle (EV) [3]. Each type of vehicle can be substituted, but the fuel cannot be substituted, given the vehicle type. The modeling framework for social cost and driving time has a similar functional form to the model presented in Parry and Small (2005). The difference from the literature is to differentiate the market and the marginal external cost between the two fuel types of vehicles. P is the pollution, and A is traffic accidents. S, P, and A do not vary over the types of vehicles, and they are exogenous to each individual. The function $u(.)$ is quasi-concave. $\varphi(.)$ and $\delta(.)$ are weakly convex functions implying disutility from pollution and accidents. All variables are in per capita terms.

Vehicle miles traveled (M) is determined based on fuel consumption (F) and vehicle characteristics (H), such as vehicle economy or vehicle size.

$$M_k = M(F_k, H_k) \tag{3.2}$$

[2]This assumption is reasonable as long as more government revenue is spent supporting EVs than ICEs. It also does not affect the second-best optimal formulas.
[3]To simplify the analysis, this paper only considers two fuel types of gas and electricity. Therefore, ICE stands for a gasoline vehicle.

where M is assumed as a quasi-concave function and differs between vehicle types of k. This function allows the consumer to select more efficient vehicles or different sizes in addition to driving less if fuel prices or taxes increase.

Driving time is a function of miles driven of k (M_k) and the inverse of the average travel speed(π), and the aggregate miles driven per capita ($\bar{M}$) as follows:

$$T_k = \pi M_k = \pi(\bar{M}) M_k \tag{3.3}$$

$$\bar{M} = \Sigma_{k=1}^{2} w_k \bar{M}_k \tag{3.4}$$

where $\pi' > 0$ so that more driving on the road leads to more congestion. $\bar{M}_k$ is aggregate miles per capita of k vehicle type. The fixed value of π followed by fixed $\bar{M}$ implies that agents do not consider their own effects on congestion. w_k is the share of vehicle k in the market. By assuming that there are two types of vehicle, ICE and EV, $w_1 = w$ and $w_2 = 1 - w$. The weight is the function of the government spending for the infrastructure, S, i.e., $w = w(S)$. The utility and share of vehicle fuel types depend on government expenditure for insufficient infrastructure, such as EV charging stations. Hence, $\frac{\partial w}{\partial s} < 0$, $\frac{\partial u_1}{\partial s} = 0$, and $\frac{\partial u_2}{\partial s} \geq 0$.

Pollution is produced from fuel consumption and miles driven. Since the two fuel types pollute differently, I distinguish the pollutants based on the fuel types. The pollution damages of P_{F_k} depend directly on fuel consumption of k. The other pollution damages of P_{M_k} depend only on miles traveled of k. The total pollution is combined of the two types of pollutants from two types of fuel vehicles:

$$P = \Sigma_{k=1}^{2} w_k (P_{F_k}(\bar{F}_k) + P_{M_k}(\bar{M}_k)) \tag{3.5}$$

where $P'_{F_k}, P'_{M_k} > 0$ and $\bar{F}_k$ and $\bar{M}_k$ is aggregate fuel consumption and mileage per capita of k vehicle type, respectively. The external cost of traffic accidents (A) depends on aggregate miles driven per capita:

$$A = A(\bar{M}) = a(\bar{M})\bar{M} \tag{3.6}$$

where $a(\bar{M})$ is the severity-adjusted accident rate per mile. Agents ignore all of their externality costs.

The agent's budget constraint is:

$$C_k + (q_{F_k} + t_{F_k})F_k + q_{H_k}H_k = I_k \tag{3.7}$$

where I_k is disposable income, t_{F_k} is tax rates on fuel k consumption, q_{F_k} is the producer price of fuel k , and q_{H_k} is the price of a vehicle having characteristics of H_k.

The government budget constraint is:

$$\Sigma_{k=1}^{2} w_k t_{F_k} F_k = G \tag{3.8}$$

$$G = S$$

The government revenue is assumed to be exogenous and constant. The constant government revenue means that both taxes change to maintain government revenue. No matter which tax is used to maximize welfare, it can choose the tax that will address the most significant externality for a given tax type. Therefore, although tax revenue may differ depending on the tax type, it does not affect the total welfare because all government revenue is passed on to consumers as it is. The revenue is handed out to consumers by spending on poor infrastructure to support the electric vehicle market. Also, it is assumed that t_{F1} does not affect demand for fuel or miles of the EV market (F_2, M_2), and vice versa. However, the total pollutants generated in both markets affect fuel consumption and driving miles.

3.2.2. The Second-Best Optimal Tax: Flat Taxes. This section provides three formulas for the second-best optimal tax of flat tax type: a gasoline tax, a flat VMT tax, and a flat VMT+gas tax. The fundamental equations are presented explicitly, and the remained derivations are provided in Appendix 3.A.1.

The welfare function (**V**) is given by the weighted sum of the indirect utility function(V_k) of the representative for each type of vehicle.

$$\mathbf{V} = wV_1 + (1-w)V_2 \tag{3.9}$$

The planner maximizes the utility by a total derivative of the utility function. Differentiating the utility for the government spending(S) with a constant government revenue, the marginal welfare change from the expenditure for the infrastructure is as:

$$\frac{d\mathbf{V}}{dS} = \frac{\partial w}{\partial S}V_1 + w\frac{\partial V_1}{\partial S} - \frac{\partial w}{\partial S}V_2 + (1-w)\frac{\partial V_2}{\partial S} \tag{3.10}$$

At the optimal, if $V_1 > V_2$, the infrastructure spending increases EV owners' utility. Otherwise, the government supports the EV market until $V_1 = V_2$.

The marginal welfare change from a tax depends on the tax imposed. The following theoretically illustrates each tax type's second-best optimal tax rate and suggests explicit formulas.

Gasoline Tax ($t^*_{F_1}$) Only the ICE holders are taxed if the government charges gasoline consumption. That is, $t_{F_2} = 0$, and it means that the equation 3.8 is $w_1 t_{F_1} F_1 = G$. Then, the marginal welfare is changed only by the gas tax (t_{F_1}) as :

$$\frac{d\mathbf{V}}{dt_{F_1}} = w\lambda(MEC_1 - t_{F_1})F_{11} \tag{3.11}$$

where λ is the marginal utility of income and

$$\begin{aligned}
& MEC_k = E^{P_{F_k}} + (\beta_k/\alpha_{FM_k})(E^{P_{M_k}} + E^A + E^C) \\
& \beta_k \equiv (\frac{dM_k/dt_{F_k}}{dF_{F_k}/dt_{F_k}})\frac{F_k}{M_k} = \frac{\eta_{MF_k}}{\eta_{FF_k}}; \quad \eta_{FF_k} = \eta_{MF_k} + \eta_{FF}^{\bar{M}}; \quad \alpha_{FM_k} \equiv F_k/M_k; \\
& E^{P_{F_k}} = \frac{\varphi' P'_{F_k}}{\lambda}; \quad E^{P_{M_k}} = \frac{\varphi' P'_{M_k}}{\lambda}; \quad E^A = \frac{\delta' A'}{\lambda}; \quad E^C = -\frac{u_T}{\lambda}\pi'\bar{M}; \\
& F_{kk} \equiv -\frac{dF_k}{dt_{F_k}}; \quad k = \{1, 2\}
\end{aligned} \tag{3.12}$$

η_{FF_k}, η_{MF_k}, and $\eta_{FF}^{\bar{M}}$ are fuel demand elasticity, VMT demand elasticity, and fuel demand elasticity with VMT held constant. All elasticities are defined in positive numbers as:

$$\eta_{FF_k} = -\frac{dF_k}{dP_k}\frac{P_k}{F_k} \qquad \eta_{MF_k} = -\frac{dM_k}{dP_k}\frac{P_k}{M_k} \qquad \eta_{FF}^{\bar{M}} = -\frac{dF_k}{dP_k}\mid_{M=\bar{M}} \frac{P_k}{F_k} \tag{3.13}$$

where P_k is the operating cost per gallon to drive ($P_k = q_{F_k} + t_{F_k}$). Holding the fuel prices leads to $\frac{dF_k}{dP_k} = \frac{dF_k}{dt_{F_k}}$, $\frac{dM_k}{dP_k} = \frac{dM_k}{dt_{F_k}}$. $1/\alpha_{FM_k}$ is miles per gallon (MPG), implying fuel economy.

In this model, α_{FM_k} is endogenous. By assumption of a constant-elasticity,

$$\alpha_{FM_k} = \alpha_{FM_k}^0 (\frac{q_{F_k} + t_{F_k}}{q_{F_k} + t_{F_k}^0})^{\eta_{FF}^{\bar{M}}} \tag{3.14}$$

The second-best optimal tax is derived from setting the equation 3.10 and 3.11 equal to zero, respectively, and holding G constant in the government budget constraint of equation 3.8 given $t_{F_1} > 0$ and $t_{F_2} = 0$. Hence, the second-best optimal gas tax is

$$t^*_{F_1} = MEC_1 \tag{3.15}$$

The second-best optimal gas tax is the marginal external cost as expressed by the equation 3.12. It has similar components in the marginal external cost (MEC) in Parry and Small (2005). The first term is the marginal external cost related to gasoline combustion. The second term is external cost related to VMT, which is the sum of marginal external costs from pollution related to driving miles, accidents, and congestion. The second term is costs per mile, so it needs to be multiplied by fuel efficiency to get the cost per gallon. Also, the marginal external cost generated from driving should be adjusted with β, the VMT demand elasticity ratio to the fuel demand elasticity. The driving distance depends on fuel consumption and vehicle characteristics. The gas tax reduces miles driven indirectly by adjusting fuel economy or vehicle size. Therefore, the marginal external cost of incurring a tax in this model is not the actual social cost. Instead, it entails the social cost that can be addressed by the tax imposed.

Flat VMT tax (t^*_v) A flat VMT tax (t_v) is a tax charging the same tax rate on both vehicle fuel types of ICEs and EVs.

To derive the second-best optimal flat VMT tax, the marginal welfare changes by the tax per mile (t_v) are as follows:

(3.16)
$$\frac{d\mathbf{V}}{dt_v} = \lambda \left[\frac{w}{\alpha_{FM_1}}(MEC_1 F_{11} - t_v M_{11}) + \frac{(1-w)}{\alpha_{FM_2}}(MEC_2 F_{22} - t_v M_{22}) \right]; \quad M_{kk} \equiv -\frac{dM_k}{dt_{F_k}}$$

If imposing a VMT tax, it directly reduces the miles driven. The second-best optimal tax is derived from setting the equation 3.10 and 3.16 equal to zero, respectively, and holding G constant in the government budget constraint of equation 3.8 given $t_v > 0$. Then, the second-best optimal flat VMT tax rate per mile is derived as follows:

$$t_v^* = \frac{\frac{w}{P_1}}{\frac{w}{\alpha_{FM_2}P_1} + \frac{(1-w)}{\alpha_{FM_2}P_2}} MEC_1 + \frac{\frac{(1-w)}{P_2}}{\frac{w}{\alpha_{FM_2}P_1} + \frac{(1-w)}{\alpha_{FM_2}P_2}} MEC_2 \tag{3.17}$$

$$P_k \equiv q_{F_k} + t_v \frac{1}{\alpha_{FM_k}}$$

This model differentiates the marginal external cost between the two fuel types. The second-best optimal flat VMT tax is the weighted sum of the marginal external cost in each market, using the fuel economy, operating cost including tax, and market share. Since we take a constant fuel economy, $\eta_{FF_k}^{\bar{M}} = 0$, implying $\eta_{FF_k}^{v} = \eta_{MF_k}^{v}$. That is, $\beta_k = 1$ is applied to calculate the marginal external cost. Since the tax rate is entailed on both sides of the equation, the flat VMT tax rate must be solved numerically for the tax given other parameters.

Flat VMT+gas Tax (t_c^*) A flat VMT+gas tax(t_c) is a combined tax, the flat VMT tax on ICE and EV with maintaining the gasoline tax policy. The second-best optimal flat VMT+gas tax has a similar formula to the flat VMT tax(t_v^*). However, part of the tax is imposed as a gas tax on ICEs, so the marginal external cost is adjusted to some extent by the gas tax rate (t_g). The second-best optimal flat VMT+gas tax would be:

$$t_c^* = \frac{\frac{w}{P_1}}{\frac{w}{\alpha_{FM_2}P_1} + \frac{(1-w)}{\alpha_{FM_2}P_2}} (MEC_1 - t_g) + \frac{\frac{(1-w)}{P_2}}{\frac{w}{\alpha_{FM_2}P_1} + \frac{(1-w)}{\alpha_{FM_2}P_2}} MEC_2 \tag{3.18}$$

The flat VMT+gas tax differs by the amount of the gas tax imposed on the ICEs. Therefore, in order to obtain the most significant social welfare change, the second-best optimal rate should be numerically solved by giving the range from zero gas tax to the second-best optimal gas tax.

3.2.3. The Second-Best Optimal Tax: Differential Taxes. This section discusses the second-best optimal taxes of differential tax types. As a tax is differentiated across more dimensions, the rates could theoretically be close to the level of optimal rate. This section first suggests a formula for a differentiated VMT tax to maximize social welfare. Also, it suggests the optimal differential combined tax, referred to as EV VMT+gas tax. The government adopts the different tax types for different fuel vehicles by introducing a VMT tax only for EVs and sustaining a gas tax policy for ICEs. The detailed derivation is provided in Appendix 3.A.2.

Differential VMT tax ($t^*_{vd_k}$) The second-best optimal differential VMT tax on vehicles by fuel type ($t^*_{vd_k}$) is a different VMT tax rate to maximize social welfare in each market.

By keeping a fuel price excluding a tax, a VMT tax makes β_k equal to 1 by $\eta_{MF_k} = \eta_{FF_k}$. To derive the second-best optimal differential VMT taxes, denote the tax rate by $t_{vd_k} = t_{F_k}\alpha_{FM_k}$, given the constant fuel economy(Parry and Small (2005)). With constant fuel economy, $1/\alpha_{FM_k}$, we can express $t_{F_k}\alpha_{FM_k}M = t_{F_k}F$. Hence, one can derive the second-best optimal tax of t_{F_k} along with t_{vd_k}. Then, the marginal welfare change is as follows:

(3.19) $$\frac{d\mathbf{V}}{dt_{F_1}} = w\lambda\left[(MEC_1 - t_{F_1})F_{11} - (MEC_2 - t_{F_2})F_{22}(\frac{F_1 - t_{F_1}F_{11}}{F_2 - t_{F_2}F_{22}})\right]$$

The second-best optimal taxes are derived from setting the equation 3.10 and 3.19 equal to zero, respectively, and holding G constant in the government budget constraint of equation 3.8 given $t_{F_1} > 0$ and $t_{F_2} > 0$. Then, the second-best optimal differential taxes per gallon are as follows:

(3.20) $$t_{F_1} = MEC_1 + (t_{F_2} - MEC_2)(\frac{\frac{P_{F_1}}{\eta_{FF_1}} - t_{F_1}}{\frac{P_{F_2}}{\eta_{FF_2}} - t_{F_2}})$$

The second-best optimal tax, t_{F_2}, has the symmetric form. The second-best optimal differential VMT tax per gallon is the equation 3.20 with replacing $\eta_{FF_k} = \eta_{MF_k}$ and $\beta_k = 1$ for each market. Then, $t_{F_k}\alpha_{FM_k} = t_{vd_k}$ is the second-best optimal VMT tax in cents per mile.

The equation 3.20 has two components: Pigouvian tax on its own market and adjusted tax rates responded by the elasticities and the tax on the other market. When elasticity is low in both markets, the tax has the same direction for each marginal external cost. That is, if a tax in one market is less than the MEC, the other market tax is required to be under the social cost in that market to maximize total welfare. As a result of derivations, all sets of the two taxes could be optimal to maximize the welfare given the economic parameter values and the other market tax. Given that the other market tax is equal to its marginal external cost to maximize welfare in that market, the tax in one market as the optimal tax set in equation 3.20 is as:

$$t^*_{vd_k} = \left[E^{P_{F_k}} + (1/\alpha_{FM_k})(E^{P_{M_k}} + E^A + E^C)\right] \alpha_{FM_k} \tag{3.21}$$

It is the marginal external cost in the market. That is, the second-best optimal differential VMT taxes are MEC in each market. The different marginal external costs of ICE and EV generate different optimal tax rates for each market.

EV VMT+gas Tax ($t^*_{EV_k}$) EV VMT+gas tax is a combined tax in which a VMT tax is levied only on EVs and a gasoline tax is levied only on ICEs. The model assumes that a tax in one market does not affect the other market directly. Hence, the EV VMT+gas tax rate for EVs ($t^*_{EV_2}$) is the differential VMT tax for EV ($t^*_{vd_2}$) at the second-best optimal rate. The EV VMT+gas tax for ICEs ($t^*_{EV_1}$) is the gas tax($t^*_{F_1}$) at the second-best optimal rate. EV VMT+gas tax also can be derived from the symmetric form of equation 3.20 by applying the second-best optimal VMT tax($t^*_{vd_2}$) to t_{F_2}, or vice versa, and adjusting it with using the fuel economy to convert the unit of the corresponding tax, gas tax or VMT tax.

All of the second-best optimal taxes are solved numerically, given the parameters at the social optimum. I use observed data instead of the optimal value for each parameter to estimate the appropriate optimal tax level. Also, all elasticities are assumed as constant.

3.2.4. Total Welfare Change. This section shows the formulas for the welfare benefits of the tax changes. The details to derive the equations are in Appendix 3.A.3. The equation 3.19 can be rewritten as:

$$\frac{1}{\lambda}\frac{d\mathbf{V}}{dt_k} = w_k(t_k^* - t_k)\left[(\frac{\eta_{FF_k}}{q_{F_k} + t_k})(\frac{P_k}{P_k^0})^{-\eta_{FF_k}} F_k^0\right] \tag{3.22}$$

where superscript 0 means initial value before charging a new tax. Given a tax type, t_k^* is the second-best optimal tax for each fuel market. That is, $t_k^* = t_{F_1}^*$ if the gasoline tax is applied, and $t_k^* = t_{vd_k}^*/\alpha_{FM_k}$ if the VMT tax is applied. t_k is the tax imposed for k fuel type market. Also, the welfare change as a proportion of initial fuel expenditure (Parry and Small (2005)), defined as production costs excluding a tax of each k type vehicle, is as:

$$\frac{1}{q_{F_k}F_k^0}\left(\frac{1}{\lambda}\frac{d\mathbf{V}}{dt_k}\right) = w_k(t_k^* - t_k)\left[(\frac{\eta_{FF_k}}{q_{F_k}(q_{F_k} + t_k)})(\frac{P_k}{P_k^0})^{-\eta_{FF_k}}\right] \tag{3.23}$$

The approximate welfare gain from raising the current tax to the tax imposed(t_k) for each fuel type market is obtained by integrating the equation 3.22. The equation 3.23 provides the welfare change as a fraction of fuel expenditure for each vehicle type market. λ is assumed constant as 1. Then, welfare from adopting the second-best optimal tax can be estimated by applying the parameter values. Total welfare change can be estimated by

$$\Delta\mathbf{V} = \frac{d\mathbf{V}}{dt_1} + \frac{d\mathbf{V}}{dt_2}. \tag{3.24}$$

3.3. Parameter Values and Data

This section describes the parameter assumptions to calculate the taxes discussed in section 3.2 and to compute the welfare change resulting from achieving the taxes. It also suggests reasonable ranges of primary parameters based on relative findings as well as the central values to obtain reasonable tax rates. Table 3.1 summarizes the parameter values for ICE and EV. It also presents maximum and minimum values of pollution from fuel consumption and mile driving, gas and VMT demand elasticities, and share of ICEs and EVs.

3.3.1. Differential Parameters by Fuel Types. Initial Fuel Efficiency $1/\alpha^0_{FM_k}$ (miles/gal). According to the 2020 Highway Statistics from Federal Highway Administration (FHWA), the average miles per gallon (MPG) of all light-duty vehicles registered in the US is 22.9 in 2020. The fuel economy for the registered electric vehicle is complicated. The National Renewable Energy Laboratory(NREL) Data[4] assumes that battery electric vehicles(BEVs) efficiency is 119 miles per gallon equivalent. For plug-in hybrid vehicles(PHEV), the electricity efficiency is 119, and the gas efficiency is 45, using electricity for 76% of driving. From the assumption of NREL, the adjusted average MPGe is 110. The 2017 National Household Travel Survey(NHTS) from the US Department of Transportation surveyed households in the US. The vehicles in the sample of NHTS are from 1977 to 2017. The survey results suggest that the average MPGe for BEV is 101.5, and the MPGe for PHEV is 41.2. Calculated using NHTS data in the same way that NREL calculated its adjusted average MPGe, the average MPGe for roads is 94.2. By taking the mean of NREL assumptions and the NHTS results, the estimated MPGe for registered electric vehicles in the US is 102.2. Hence, this analysis takes 22 for the parameter values of ICE's MPG and 102 for EV's MPGe.

Pollution damages, fuel-related, $E^{P_{F_k}}$(cents/gallon). The pollution damage depending on fuel consumption is relative to the carbon dioxide resulting from global climate change. The Energy Information Administration(EIA) estimates 19.37 lbs of CO_2 per gallon from motor gasoline. The social cost of carbon varies between analyses. The Environmental Protection Agency suggests $42 per ton for the social cost of CO_2 for 2020 with a 3 percent discount rate, leading to 41 cents/gal. This parameter value is consistent with the recent work (Langer et al. (2017), Holland et al. (2016)). However, this value is much higher than Parry and Small (2005), which

[4]Borlaug, Brennan; Muratori, Matteo; Gerdes, Mindy; Salisbury, Shawn (2020): Levelized Cost of Charging Electric Vehicles. National Renewable Energy Laboratory. 10.7799/1661199

used \$25 per tC based on the literature results in the 1990s, suggesting 9 cents/gal in 2020 prices. Mitropoulos et al. (2017) adopt \$27 per tC for the cost of CO_2 and other GHGs. Tong and Azevedo (2020) assumes \$36 per tC. Therefore, I take the central value of the final estimated social cost of fuel consumption to be 25 cents/gal. Also, given the wide range of the cost of GHGs, I take the range of 10-40 cents/gal of the marginal externality for the sensitivity analysis. Since EVs do not burn fuel directly, the social cost of consuming fuel from driving EVs is zero. Instead, the social cost from EVs is included in the pollution damages relative to miles driven, as described next.

Pollution damages, distance-related, $E^{P_{M_k}}$ (cents/mile). There are limited evaluations of the externality costs of alternative fuel vehicles. Holland et al. (2016) estimates the environmental benefits of specific EV models compared to the foregone gasoline vehicles. Tong and Azevedo (2020) provides the marginal cost of climate change and air pollution by vehicle and fuel types. The distance-related pollution damages parameters for ICEs and EVs are taken from Tong and Azevedo (2020). The social costs in this literature include energy extraction, fuel production and transportation, vehicle use, and the manufacturing of lithium-ion batteries for EVs. Social costs for both vehicle markets are weighted averages using the share of vehicle types of the 2017 NHTS, such as passenger cars or SUVs, and updated to 2020 prices. The climate change relative to greenhouse gases considers damages from CO_2, CH_4, and N_2O. Other air pollutants entail emissions of the five pollutants: SO_2, NO_X, CO, $PM_{2.5}$, and $VOCs$. To apply the corresponding value of ICEs to EVs, air pollution damages are assumed to be distance-related pollution from driving ICEs. The sum of climate change and air pollution damages is proportional to miles driven with EVs. Therefore, the pollution damages associated with distance traveled are assumed to be 0.85 cents/mile for ICEs and 1.8 cents/mile for EVs.

Fuel Price and Tax, $q_{F_k}, t^0_{F_k}$ (cents/gallon). The Alternative Fuels Data Center(AFDC) provides the average retail fuel prices. I take the prices from 2016 to 2020, which are converted to real 2020 prices. The producer gasoline price is an average retail gasoline price minus taxes. The electricity price is an average retail electricity price in gasoline gallon equivalents. Each price for ICEs and EVs is 202 cents/gallon and 146 cents/gallon, respectively. The gasoline tax is the sum of the federal and state-weighted average taxes based on gross gallons taxed, provided by FHWA. It is 48 cents/gallon. The initial tax for EVs is zero.

Fuel Consumption, F_k^0 (10^9 gallon). For ICEs, I use the product supplied to the finished motor of EIA gasoline data for fuel consumption (139.13×10^9 gallon) for the average of 2016-2020. Since there are no detailed data for the electric consumption for EVs, I estimate it by using annual vehicle traveled in miles from FHWA for the average of 2016-2020 ($3,158 \times 10^9$ miles), the shares of EVs(0.01), and the average MPGe (102). The estimated initial fuel consumption for EVs is 0.31×10^9 gallon. The same calculation for gasoline consumption has similar values to the observed data.

Weight of Vehicle by Fuel-type, w_k FHWA and AFDC provide the number of motor vehicles and registered EVs, respectively. Based on the data, EV share in 2020 is 0.57% on the road. For this analysis, the shares of 1% for EVs and 99% for ICEs are supposed at first. Additionally, the range of EV share up to 50% is considered for the sensitivity analysis.

3.3.2. The Common Parameter Values. The following parameter values are assumed to be the same for ICEs and EVs.

External Accident Cost, E^A (cents/mile). The marginal accident costs could vary over drivers and vehicle types, but there is no evidence whether a specific fuel type vehicle driver has higher risks than the other. Therefore, it is assumed to be the same for the two fuel types of vehicles. The FHWA estimates the marginal external costs of crashes, which considers two components, crash costs uncovered by drivers and variable costs depending on traffic levels. It is 1.97 cents per mile, with a range of 1.11-6.12 cents per mile. I update the result to 2020 prices so that the value of the common parameter for external accident cost is 3 cents/mile.

External Congestion Cost, E^C (cents/mile). The marginal congestion costs could vary over locations depending on traffic, not fuel types. Therefore, it is assumed to be the same regardless of the fuel type. Langer et al. (2017) assumes a total congestion externality of 12.9 cents/mile for urban and 2.3 cents/mile for rural. The Highway Cost Allocation Study of FHWA, released in 2000, suggests that marginal external costs for congestion are 4.48 cents/mile for automobiles and 4 cents/mile for Pickup and Vans, respectively. I take 6 cents per mile by updating the middle value to 2020 prices.

Elasticities, η_{FF}, η_{MF} Several studies of gasoline demand (Goetzke and Vance (2021), Dimitropoulos et al. (2018), Levin et al. (2017), Gillingham and Munk-Nielsen (2019)) find gasoline price elasticities between 0.03 and 0.58. Also, the most relevant paper, Parry and Small (2005), uses 0.55 for that parameter. Based on the literature, I adopt 0.4, which is less elastic for gasoline prices than Parry and Small (2005) by considering the recent study. Also, the latest works (Su (2015), Dimitropoulos et al. (2018), Alberini et al. (2021)) provide the central value for the VMT elasticity to be 0.20. These parameter values imply that the ratio of two elasticities, β, is 0.5.

TABLE 3.1. **Parameter Assumptions**

Parameter		ICE	ICE min	ICE max	EV	EV min	EV max
Initial fuel efficiency	$1/\alpha^0_{FM}$ (MPG)	22	-	-	102	-	-
Pollution, fuel-related	E^{P_F} (cents/gal)	25	10	40	0	0	0
Pollution, miles-related	E^{P_M} (cents/mile)	0.85	0.425	1.275	1.8	0.9	2.7
Accident cost	E^A (cents/mile)	3	-	-	3	-	-
Congestion cost	E^C (cents/mile)	6	-	-	6	-	-
Gas elasticity	η_{FF}	0.40	0.30	0.50	0.40	0.30	0.50
VMT elasticity	η_{MF}	0.20	0.15	0.25	0.20	0.15	0.25
VMT portion of gas elasticity	β	0.5	-	-	0.5	-	-
Producer price of gas	q_F (cents/gal)	202	-	-	146	-	-
Initial gas tax	t^0_F (cents/gal)	48	-	-	0	-	-
Weight	w	0.99	0.5	-	0.01	-	0.5
Total fuel consumption	F^0 (10^9 gallon)	139.13	-	-	0.31	-	-

Notes: The sources of the assumption are described in the text.

3.4. Empirical Results of the Second-Best Optimal Tax

Section 3.2 demonstrates the explicit functional forms of the second-best optimal gas tax, flat VMT, and flat VMT+gas taxes for a flat-tax type. Also, it suggests differential tax types such as differential VMT tax and EV VMT+gas tax for differential tax type. This section provides empirical results of the diverse tax types by applying the baseline parameters in Table 3.1. Also, it discusses the second-best optimal tax as the EV share increases.

3.4.1. The Second-Best Optimal Tax Rates of Flat-tax. Table 3.2 gives the estimated fuel economy, the marginal external cost and its components, and the second-best optimal tax rates by tax types. It also provides the tax rates in two units of cents per gallon and cents per mile to compare the tax rates in the same unit. Under the gas tax, the marginal external cost is 255.8 cents/gal based on the baseline parameters described in section 3.3 and the estimated fuel economy given the gas tax rate. The second-best optimal gasoline tax is 140.4 cents/gal. Given the much higher tax than 48 cents/gal of the average current tax rate, the consumers adjust their vehicle fuel economy up to 23.4 miles per gallon. By improving fuel economy, a gasoline tax reduces mileage only indirectly. The lower VMT elasticity compared to the fuel consumption elasticity reduces the gasoline tax to correct the market failure as much as the VMT demand elasticity ratio to fuel demand elasticity, i.e., β. It decreases the marginal external cost to incur the tax to 140.4 cents/gal, the second-best optimal gas tax. The difference between the marginal external cost and the tax rates implies the inefficiency of the gas tax in fixing the market failure. This tax falls within the range of the optimal tax rates estimated in the literature. Parry and Small (2005) suggests 101 cents/gal, but the recent work, Bjertnæs (2019), gives a much higher optimal gas tax, 236 cents/gal. Knittel and Sandler (2018) provides the optimal differential tax with the range of 23 - 91 cents/gal by existing vehicle vintages in California.

When introducing a VMT tax for both ICEs and EVs, policymakers should decide whether to tax them differently or uniformly. This paper first discusses a more basic tax type, a flat VMT tax. The flat VMT tax is a tax that charges uniformly on two fuel-type vehicles. A VMT tax

TABLE 3.2. **Second-Best Optimal Taxes: Flat Tax Types**

	Gas tax		Flat VMT tax		Flat VMT+gas tax	
	ICE	EV	ICE	EV	ICE	EV
Estimated MPG	23.4	102.0	22.0	102.0	22.0	102.0
MEC (cents/gal)	255.8	1,101.6	241.7	1,101.6	241.7	1,101.6
- Fuel pollution	25.0	0.0	25.0	0.0	25.0	0.0
- Miles component	19.9	183.6	18.7	183.6	18.7	183.6
- congestoin	140.6	612.0	132.0	612.0	132.0	612.0
-Accident	70.3	306.0	66.0	306.0	66.0	306.0
Components of the Tax (cents/gal)	140.4	-	241.6	1,120.3	242.3	936.6
- Fuel pollution	25.0	-	25.0	0.0	25.1	0.0
- Miles component	10.0	-	18.7	186.7	18.7	156.1
- congestoin	70.3	-	132.0	622.4	132.3	520.4
-Accident	35.1	-	66.0	311.2	66.2	260.2
Optimal tax for each tax type						
Gas tax (cents/gal)	140.4	-	-	-	40.3	
VMT tax (cents/mile)	-	-	11.0	11.0	9.2	9.2
Tax equivalent						
(cents/mile)	(6.0)	-	-	-	(1.8)	-
(cents/gal)	-	-	(241.6)	(1,120.3)	(202.0)	(936.6)

Notes: MEC for EVs is converted in cents/gal using estimated MPG. Components of the tax only incorporate the marginal external cost to be corrected by the tax. The components are calculated by the MEC ratio of each tax.

directly impacts miles driven, unlike a gas tax. Since a VMT tax directly reduces miles driven, the consumers keep their vehicle efficiency the same. The constant vehicle efficiency leads to slightly less marginal external cost per gallon than the cost under a gas tax. The second-best optimal flat VMT tax is between the marginal external cost of two markets when the cost is converted into the same unit of the VMT tax, i.e., cents per mile. The marginal external cost is 241.7 cents per gallon for ICEs and 1,101.6 cents per gallon for EVs. The value of MEC for EVs is converted from the cost in cents per mile using the estimated MPG. If converting them to the unit of cents/mile, the MEC is 11.0 and 10.8 cents/mile for driving ICEs and EVs, respectively. The flat VMT tax is the average marginal cost in both markets adjusted by the weight, which corporates each vehicle's market share, fuel price, and fuel economy. The primary factor of the adjusted weight is the market share. A small EV share of 1% results in the second-best flat VMT tax rate being close to the marginal external cost of driving ICEs. Therefore, the flat VMT tax rate is 11.0 cents/mile. It produces more burden on EV owners since the tax is higher than the marginal external cost in that market. Instead, the tax on ICE owners is slightly less than the social cost of the market. However, since the VMT tax reflects the externality cost directly, the second-best optimal flat VMT tax of 241.6 cents/gal for ICEs, converted in the same unit of a gas tax, is higher than the second-best optimal gas tax.

The last primary tax type is a flat VMT+gas tax. It is a flat VMT tax in addition to a gasoline tax, which is the tax rate to maximize social welfare under the constraints of the tax type. The tax rates are estimated numerically. The second-best flat VMT+gas tax is a flat VMT tax of 9.2 cents/mile and the gas tax of 40.3 cents/gallon[5]. The gas tax has been imposed as 48 cents/gallon. The initial marginal benefit from introducing a VMT tax is less than a gas tax because of the lower ratio of VMT demand elasticity to the fuel price elasticity and the law diminishing marginal utility. The VMT demand elasticity tends to be less than the fuel price elasticity. Most literature suggests that the VMT demand elasticity ratio of the fuel demand elasticity is less than 0.5 (Parry and Small (2005)). It requires a much higher VMT tax than a gas tax at the optimal. The law diminishing marginal utility causes higher marginal benefit from newly introducing a gas tax than a VMT tax. Therefore, maintaining the gas tax to a certain extent prevents the loss of welfare caused by eliminating the already levied gas tax. However, a gas tax indirectly corrects market failures by adjusting the fuel economy or size of vehicles. The inefficiency of the gas tax requires the introduction of a VMT tax instead of lowering the gas tax when introducing a flat VMT+gas tax. By imposing only a portion of the tax on ICE as the gas tax, the tax burden of electric vehicles is reduced. That is, the difference between the externality cost and the tax on EV is less than the second-best optimal flat VMT tax.

[5]To simplify the estimation, the fuel economy is assumed to be constant even in keeping with the gas tax policy. Otherwise, the fuel economy would deteriorate under the decreased gas tax rate from the current gas tax. It might not be plausible, considering that fuel economy tends to be improved. Also, the change in fuel economy under this gas tax rate is ignorable.

3.4.2. The Second-Best Optimal Tax Rates of Differential Tax. Table 3.3 provides the empirical results of the differential tax rates based on the fundamental parameter values. The first type is differential VMT tax, which is a VMT tax imposed differently on each fuel type of vehicle. Considering that it has more dimensions to tax, this type of VMT tax could improve social welfare more than a flat VMT tax type. The differential VMT tax applies the heterogeneous environmental cost from each type of vehicle. The marginal external cost from ICEs is 241.7 cents/gal, while the cost from EVs is 1,101.6 cents/gal. The EVs' MPG is much higher than ICEs, and the fuel economy is constant in both markets. It augments the externality cost per gallon from EVs. The second-best optimal differential VMT tax in each market is the same as the marginal external cost from each vehicle. With the baseline parameters, the differential VMT taxes on ICEs and EVs are 11.0 and 10.8 cents/mile, respectively. These tax rates mirror the Pigouvian tax rate in each market. Also, it is a higher tax rate for ICEs than the optimal gas tax in the same unit.

Replacing the gas tax with the VMT tax requires retrofitting all existing vehicles to track mileage, which could create cost issues when implementing the policy. Therefore, it is interesting to consider a VMT tax only on EVs with maintaining a gas tax policy, referred to as an EV VMT+gas tax. Since each market is unaffected by the other market's tax by assumption, the EV VMT+gas tax reflects the second-best optimal tax rates in each market. The optimal tax set can also be derived from the equation 3.20. The gas tax for ICEs is 140.4 cents/gal, the second-best optimal gas tax rate to correct the market failure. The VMT tax for EVs is 10.8 cents/mile, the second-best optimal differential tax rate for EVs. That is, the gas and VMT taxes in the EV VMT+gas tax address as much externality as the second-best gas tax on ICE and the differential VMT tax on EV, respectively.

3.4.3. Tax Rates by EV share. Figure 3.1 shows the changes in the second-best optimal tax rates as EV share grows up to 50% by tax types: the gas tax, flat VMT tax, and flat VMT+gas tax. The tax in each fuel type market only impacts the own market demand for driving and fuel consumption by the assumption. Also, under a gas tax policy, there is a single tax only on ICEs.

TABLE 3.3. **Second-Best Optimal Taxes: Differential Tax Types**

	Differential VMT tax		EV VMT+gas tax	
	ICE	EV	ICE	EV
Estimated MPG	22.0	102.0	23.4	102.0
MEC (cents/gal)	241.7	1,101.6	255.8	1,101.6
- Fuel pollution	25.0	0.0	25.0	0.0
- Miles component	18.7	183.6	19.9	183.6
- congestoin	132.0	612.0	140.6	612.0
-Accident	66.0	306.0	70.3	306.0
Components of the Tax (cents/gal)	241.7	1,101.6	140.4	1,101.6
- Fuel pollution	25.0	0.0	25.0	0.0
- Miles component	18.7	183.6	10.0	183.6
- congestoin	132.0	612.0	70.3	612.0
-Accident	66.0	306.0	35.1	306.0
Optimal tax for each tax type				
Gas tax (cents/gal)	-	-	140.4	-
VMT tax (cents/mile)	11.0	10.8	-	10.8
Tax equivalent				
(cents/mile)	-	-	(6.0)	-
(cents/gal)	(241.7)	(1,101.6)	-	(1,101.6)

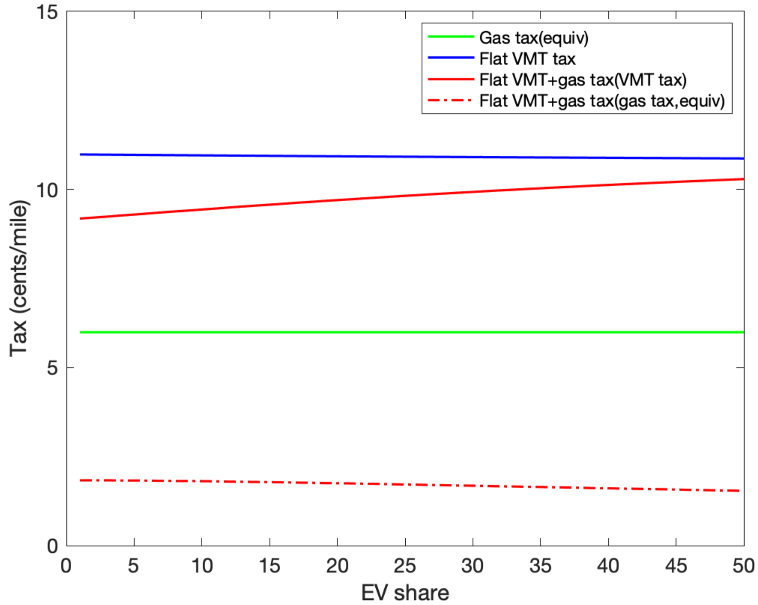
Notes: MEC for EVs is converted in cents/gal using estimated MPG. Components of the tax only incorporate the marginal external cost to be corrected by the tax. The components are calculated by the MEC ratio of each tax.

Therefore, the second-best optimal gas tax without charging any tax on EVs is consistent at 140.4 cents/gal, regardless of EV share in the market. Compared with other taxes, the tax rate is 6 cents/mile converted to the same units as the VMT tax.

The second-best optimal flat VMT tax decreases slightly to close to the externality cost of EVs as EV penetration grows. When the EV share reaches around 40%, the flat VMT tax rate becomes the mean of each social cost of ICEs and EVs, and it is continuously close to the marginal external cost in the EV market as EVs grow.

The second-best optimal flat VMT+gas tax has two factors of the tax. One is the VMT tax, and the other is the gas tax. The VMT tax rate to be optimally combined increases as EVs grow. The flat tax primarily reflects a weighted sum of two markets' social costs after deducting the amount as much as the gas tax, which reduces the legitimacy of imposing the tax on miles with

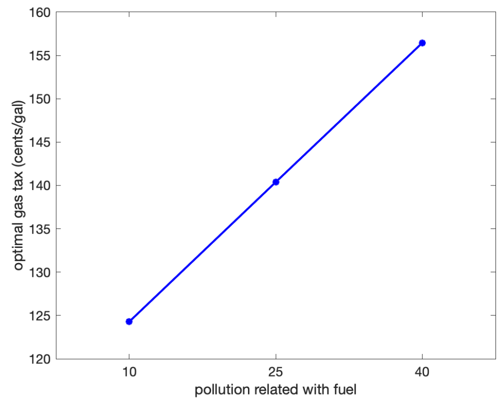
FIGURE 3.1. The Second-Best Optimal Taxes as EV Share Increases: Flat Tax Types



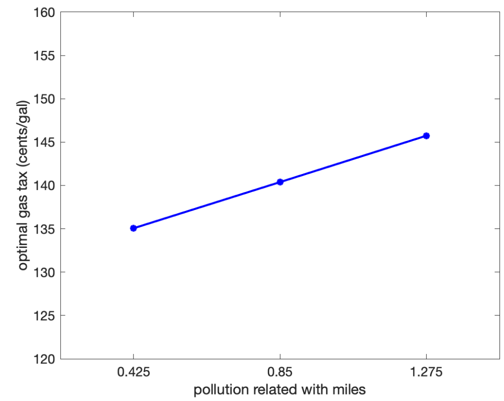
ICE. Because the effect of the deduction is diluted as EV share increases, the VMT tax rate to be combined is close to the second-best optimal flat VMT tax rate as EV grows. Interestingly, the gas tax portion decreases as the EV grows. Although the gas tax is less efficient than the VMT tax, the flat VMT+gas tax retains a portion of the gas tax to avoid losses from the abolition of the gas tax. However, as EV share increases, the benefits of introducing a VMT tax offset the losses from lower gas taxes. Eventually, the role of the gasoline tax will gradually diminish. When EVs comprise half the vehicle market, the optimally combined tax increases from 9.2 to 10.3 cents/mile and 40.3 to 33.8 cents/gallon for a flat VMT and gas tax, respectively.

Differential VMT tax and EV VMT+gas tax do not vary over the EV share. The differential VMT taxes only internalize each market failure. Regardless of the EV growth, the VMT taxes are 11 cents/mile and 10.8 cents/mile for ICEs and EVs, respectively. The EV VMT+gas tax also entails each external cost, but the different tax type applies to other fuel vehicles. Given the second-best current gas tax rate of 140.4 cents/gal for ICEs, the tax rate from the optimal tax set is 10.8 cents/mile for EVs. These taxes are consistent with EV growth.

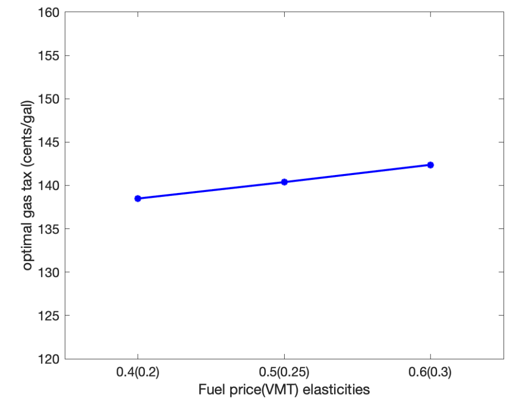
Figure 3.2. Sensitivity Analysis: The Second-Best Optimal Gasoline Tax



(a) Pollution relative to Fuel Consumption

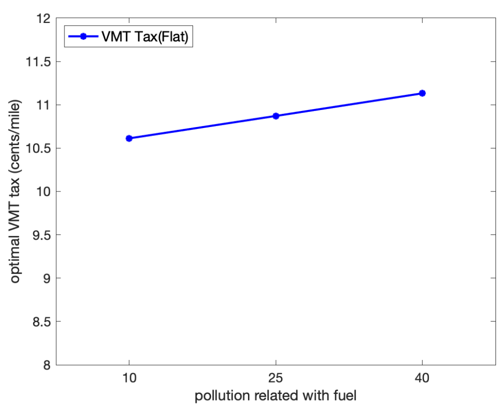


(b) Pollution relative to Miles Driven

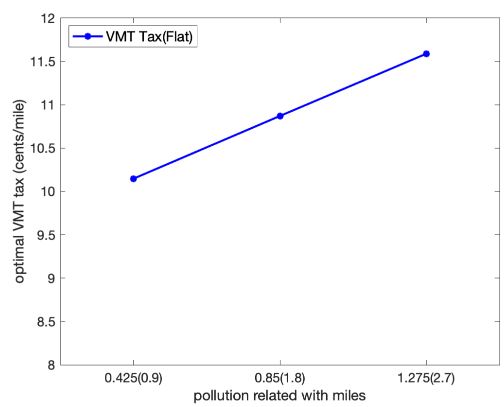


(c) Fuel Price and VMT Elasticity

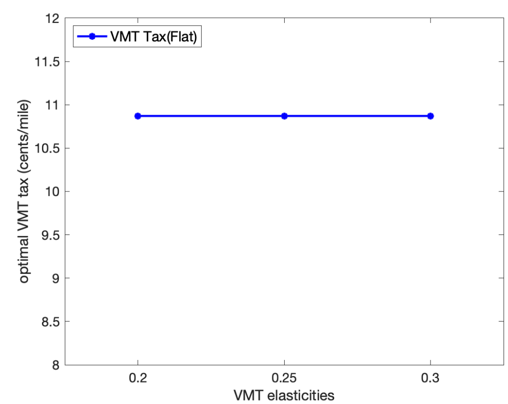
Figure 3.3. Sensitivity Analysis: The Second-Best Optimal Flat VMT Tax



(a) Pollution relative to Fuel Consumption



(b) Pollution relative to Miles Driven



(c) Fuel Price and VMT Elasticity

3.4.4. Sensitivity Analysis to Parameter Values. This section represents the sensitivity of the second-best optimal taxes suggested in section 3.4.1 and 3.4.2 with varying three primary parameters to determine the tax rates individually. The formulas to calculate the taxes have three components: the marginal external cost relative to fuel consumption, the cost relative to miles driven, and fuel or VMT elasticities. The sensitivity analyses are conducted based on the parameter values of fuel-related pollution, miles-related pollution, and the elasticities holding the ratio of β. Table 3.1 shows the range of the parameter values. The literature suggests diverse fuel-related pollution values, so a comparatively wide parameter range is used. Figure 3.2 and 3.3 show that the results vary by around 124 - 156 cents/gal of the gas tax and 10.2-11.6 cents/mile of the flat VMT tax at the second-best optimal tax rates. The taxes of other types discussed would have a similar range to this sensitivity analysis with various parameter values. The second-best optimal gas tax rates are more sensitive to fuel-related pollution, while the second-best optimal flat VMT tax varies more to miles-related pollution. All results are relatively less sensitive to the fuel price or VMT demand elasticities than the other parameter values. In constructing the parameter values, the VMT demand ratio of gasoline demand, β, is consistent.

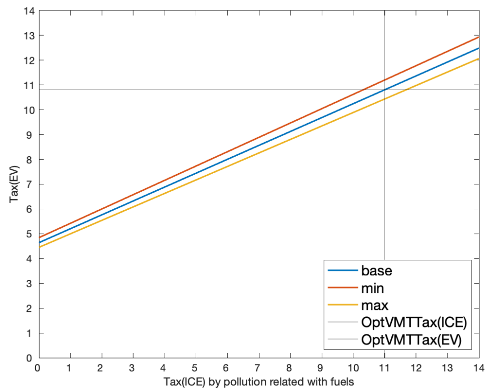
Figure 3.4 shows the sensitivity of the optimal set of the differential taxes for each fuel type market when the tax deviates from the second-best optimal rates. Both tax rates are less or higher than the second-best optimal rates. Suppose the tax for ICEs differs from the optimal value given the marginal external cost in that market. Then the alternative EV tax rate is optimally calculated given the economic values in the other market according to the equation 3.20. The taxes in the optimal tax set are proportional to each other. That is because a tax does not directly address the negative externalities of the other market. The marginal utility of the welfare function is diminishing, and both markets have similar VMT elasticities and externality costs. If the tax on ICEs is lower than the marginal external cost in the ICE market with the low elasticity of VMT demand in both markets, the tax for the EV market of the optimal tax sets is also lower than the EVs' social cost. Suppose the VMT elasticities and marginal external cost are similar in two markets.

The tax in each market would not be set to address externalities in the other market, as the tax is assumed not to affect demand for fuel and mileage in the other market. Instead, the two markets are linked by total external cost. If driving cost in one market is significantly higher than in the other market, the demand for driving in the other market will surge more asymmetrically by augmenting total externality. It possibly exacerbates overall welfare change by the law of diminishing marginal utility. Therefore, the tax does not compensate for other tax rates. Instead, taxes tend to reduce the price gap in fuel costs, maximizing welfare benefits. Also, the tax for EVs is higher than the tax for ICEs. The fuel price of driving ICEs is higher than that of driving EVs. Since the large price gap reduces the total welfare given the same utility function, the VMT tax on EVs is higher than the tax for ICEs.

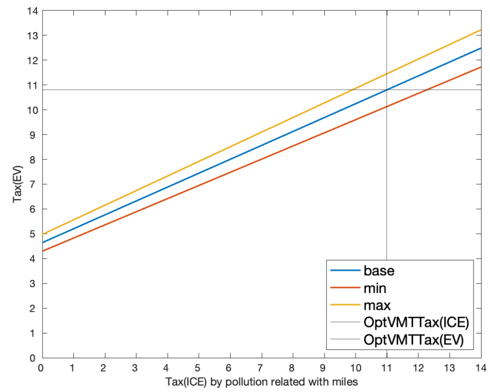
If the parameter value of pollution relative to miles driven is adjusted for two markets at the same rates, i.e., decreased by 50% for the minimum value and increased by 150% for the maximum value, the tax on EVs varies more to the parameter values compared to the tax on ICEs. The higher value of fuel-relative pollution in ICE requests a higher tax given the tax for EVs. Given the same tax on ICEs, raising the pollution associated with miles by the same percentage in both markets would result in a higher EV tax.

Meanwhile, the optimal tax sets of base parameter values are linear in taxes by assuming the elasticity of each market is the same, but applying different VMT elasticities derives non-linear relation of the optimal tax set. The higher the elasticity, the smaller the tax change. However, the sign for the difference between tax and marginal cost is the same in both markets. If the EV tax is less than the marginal external cost of the EV market, the ICE tax is also less than that cost in the ICE market. It maximizes welfare by avoiding distortion of market demand due to large price gaps. So if the tax is greater than the external cost, the higher the elasticity, the less the tax, and vice versa.

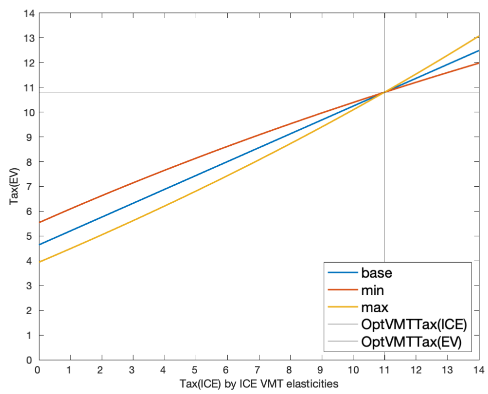
Figure 3.4. The Optimal Tax Set of Differential VMT Tax (cents/mile) in case of Deviation from the Second-Best Optimal Tax Rates



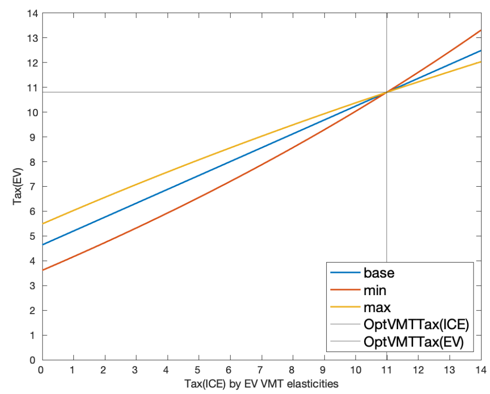
(a) Pollution related with Fuel Consumption



(b) Pollution related with Miles Driven



(c) ICE VMT Elasticity



(d) EV VMT Elasticity

3.5. Welfare Effects of the Second-Best Optimal Taxes

3.5.1. Welfare Change by Tax Types. The second-best optimal tax is the one that maximizes welfare, given the type of tax. Therefore, taxes may not be optimal for each market's welfare function. Figure 3.5 shows the path of welfare change by the tax rates in the ICE market. The gas tax partially impacts the miles driven by adjusting the vehicle's fuel economy. Therefore, one of the primary components to set the optimal value is the VMT elasticity ratio to the fuel elasticity. The baseline parameter value of β is 0.5, which deviates the optimal gas tax rates from the actual marginal external cost of ICEs. Instead, comparably higher fuel demand elasticity provides higher marginal benefit but faster diminishing the marginal utility at the initial fuel consumption than the VMT tax. Therefore, the second-best optimal gas tax is much less than other tax types.

A flat VMT tax and a differential VMT tax have the same welfare function, resulting in the same welfare change path over tax rates. The differential VMT tax gives the highest welfare gain under the function of its market, but the flat VMT tax does not. The β ratio to derive a VMT tax is one since the tax has the same impact on fuel consumption and miles driven. It leads to higher second-best optimal VMT tax rates than the gasoline tax in the same unit. Also, given the parameter value, the marginal benefit according to the VMT tax rate is lower than the gasoline tax at the beginning. Instead, the VMT tax gradually reduces marginal welfare until it reaches the second-best optimal tax level. Hence, the VMT tax has less welfare change at the beginning, but the welfare change is more significant than the gas tax as the tax rates increase.

The welfare change path of the flat VMT+gas tax is the combined path of the welfare function of the gas tax and the VMT tax. It is the same as the gas tax until it reaches the best gas tax to be combined. After then, the additional VMT tax follows the exact shape of the VMT tax welfare change. The level of welfare change can be higher than applying only the VMT tax rate. Intuitively, the flat VMT+gas tax could internalize fuel-related pollution as much as the gas tax imposed. Also, the construction of the flat VMT+gas tax could reap the additional benefit of the VMT tax, which directly impacts the miles driven without distortion. Most empirical studies suggest that β is less than 0.5. As long as β is less than 0.5, the flat VMT+gas tax gives a higher welfare path than the VMT tax. Otherwise, the flat VMT+gas tax would give at least the same welfare path to the VMT tax by the construction. The EV VMT+gas tax's welfare uses the gas tax's welfare function in the ICE market.

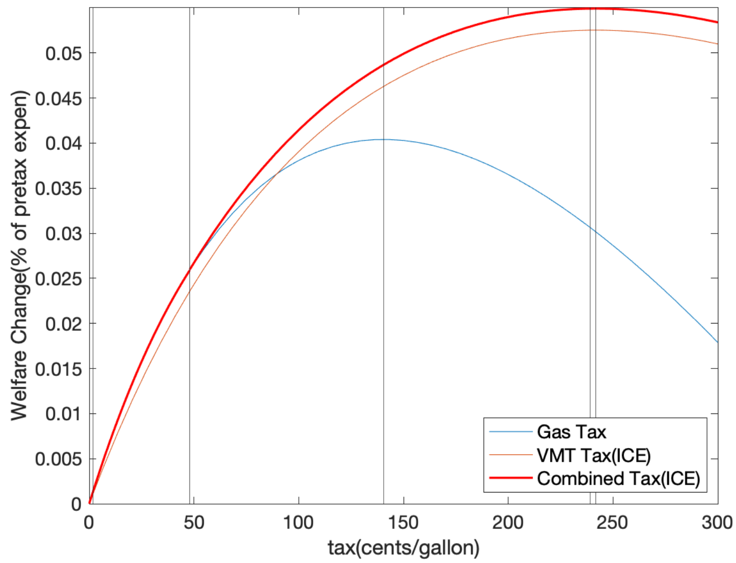
Figure 3.6 plots the welfare change over the tax rates in the EV market. The welfare path for the EV market is the same for all types of taxes as the construction. The welfare change path of the VMT tax for EVs has similar shapes to the path of the VMT tax for ICEs. However, it has a much higher welfare change level from the tax change. That is because the EV tax, expressed in cents per gallon, is much higher than the ICE tax, reflecting their higher MPG. The flat VMT tax has the same path but is higher than the second-best optimal differential VMT tax for EVs. The flat VMT+gas tax also has the same path of welfare change as the VMT taxes, but it is less than the second-best optimal VMT tax rates. The weight of EVs to derive the flat tax rates is much less than that of ICEs. It leads that the flat VMT tax rate, close to the MEC of ICEs, is higher than the differential VMT tax for EVs. However, the flat VMT+gas tax incorporates the external cost after being controlled by the imposed gas tax. It causes a less flat VMT tax rate for two markets than the VMT taxes. The second-best optimal EV VMT+gas tax is the same as the differential VMT tax rate for EVs. With the same welfare function, the change in welfare is the largest in the order of differential VMT tax, EV VMT+gas tax, flat VMT tax, and flat VMT+gas tax in the EV market.

Based on the welfare function given diverse tax types, Table 3.4 describes the welfare changes from adopting the second-best optimal tax rates. The second-best optimal gasoline tax generates the welfare benefits of $8.1 billion when the tax rate is increased from 48 cents/gallon of the current tax rate to 140.4 cents/gallon. Welfare change following the introduction of the VMT tax is calculated as the sum of the integration of the gas tax welfare function from the current gas tax rate to zero and the integration of the VMT tax welfare function from zero to the VMT tax. The flat VMT tax at the second-best optimal rate gives $14.8 bn. It is a much more significant welfare gain than the gas tax at the second-best optimal level. It implies the efficiency of adopting a VMT tax by correcting the market failure directly. The flat VMT+gas tax has even higher benefits, around $16.2 bn, than the welfare change of the flat VMT taxes at the second-best optimal tax rate. Welfare changes from the flat VMT+gas tax have the largest welfare changes as the tax type can incorporate higher marginal gains by the construction.

A differential VMT tax would be expected to improve social welfare more than a flat VMT tax, but it is noteworthy that it provides only slightly more welfare gains than the flat VMT tax at the second-best optimal rate. The welfare change is around $14.8 bn, close to the changes from adopting the flat VMT tax. Most vehicles on the road, around 99%, are ICEs in the baseline parameters; hence the total welfare effects are impacted mainly through the ICE market. It causes similar welfare effects of differential VMT tax and flat VMT tax. Meanwhile, the welfare benefit of $8.1bn from adopting the EV VMT+gas tax is similar to the gains from increasing the gas tax to the second-best optimal rate. The EV VMT+gas tax gives two benefits raising the gas tax for ICEs and introducing the VMT tax for EVs. The tiny EV share of 1% leads to minor welfare effects from the EV market. Hence, the gains in welfare are almost from ICE markets by raising the gas tax to the second-best optimal rate.

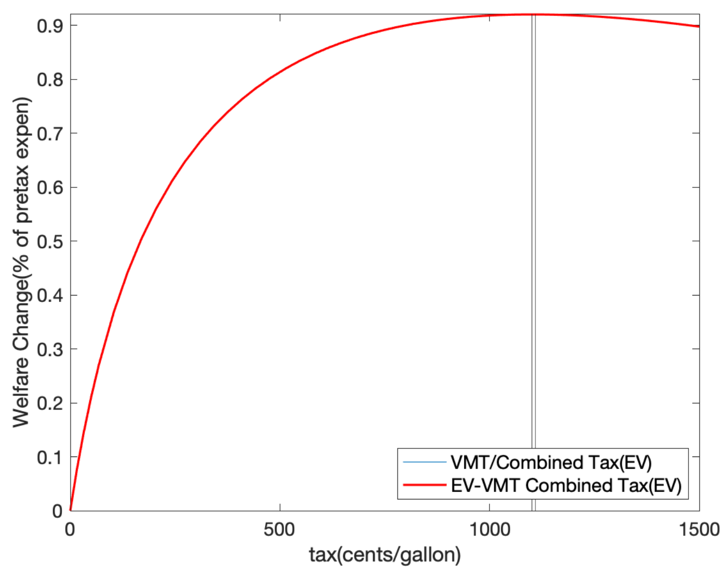
Table 3.4 also presents the projected change in government revenues due to the adoption of the tax. Assuming that the government budget constraint is fully integrated into the welfare function, the amount of tax revenue does not affect the change in total social welfare. However, it may affect the validity of tax rate applications. The flat VMT, flat VMT+gas, and differential VMT taxes generate more than twice as much government revenue as gas or EV VMT+gas taxes. Meaning the former may be more difficult to adopt than the latter.

FIGURE 3.5. Welfare Change by Tax Rates and Types (ICE)



Notes: Welfare change refers to the change in welfare when different tax rates by tax types are applied for each welfare function described in the text.

FIGURE 3.6. Welfare Change by Tax Rates and Types (EV)



Notes: Welfare change refers to the change in welfare when different tax rates by tax types are applied for each welfare function described in the text. There is only one function to calculate welfare change for EVs because EVs can only be charged by the VMT tax type.

TABLE 3.4. **Welfare Effects: The Second-Best Optimal Taxes**

	Gas tax		Flat VMT tax		Flat VMT+gas tax		Differential VMT tax		EV VMT+gas tax	
	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV
Gas tax(cents/gallon)	140.4	-	-	-	40.3	-	-	-	140.4	-
VMT tax(cents/mile)	-	-	11.0	11.0	9.2	9.2	11.0	10.8	-	10.8
Welfare change(% of pretax expen)	2.87	0.00	5.27	1.84	5.75	1.83	5.27	1.84	2.87	1.84
Pretax expenditure ($bn/year)	281.05	0.45	281.05	0.45	281.05	0.45	281.05	0.45	281.05	0.45
Estimated welfare change ($bn/year)	8.07	0.00	14.82	0.01	16.15	0.01	14.82	0.01	8.07	0.01
Total estimated welfare change ($bn/year)	8.07		14.83		16.16		14.83		8.08	
Estimated revenue change ($bn/year)	123.28	0.00	275.17	3.47	276.15	2.90	275.26	3.41	131.28	3.41
Total estimated revenue change($bn/year)	123.28		278.64		279.05		278.67		134.69	

Notes: The pre-tax expenditure of fuel is calculated by multiplying the producer fuel price(q_F) by the total initial fuel consumption(F^0)

3.5.2. Welfare Changes by EV shares.

3.5.2. Welfare Changes by EV shares. This section describes how the welfare effects change as the penetration of EVs grows. Figure 3.7 describes the total welfare change of the second-best optimal taxes as EVs grow. One of the primary components to calculate the welfare change is fuel consumption. As EVs grow, it is assumed that initial fuel expenditures are adjusted by the amount of market share[6]. Since gasoline tax is only imposed on ICEs, the total social benefit is decreased as the weight of ICEs decreases. However, all the other types of taxes tend to increase the welfare change as the EV share increases. As the EV share increases, the tax impact on overall welfare in ICEs decreases. Because the reduced welfare gain in the ICE market is greater than the increased gain in the EV market, the total welfare gain from the VMT taxes and flat VMT+gas tax initially decreases. However, when EVs play a significant role, overall welfare increases as the benefits offset the reduced welfare benefits of ICEs. Imposing a tax on miles in both markets has similar welfare changes regardless of the tax types because of their similar tax rates. The flat VMT+gas tax has even slightly higher total welfare, but as the share of ICEs decreases, the welfare change level is close to the benefit of adopting the VMT taxes. The VMT taxes and flat VMT+gas tax effects are very similar at an EV share of approximately 50%.

On the other hand, introducing an EV VMT+gas tax will obtain welfare change almost from ICE markets when the EV share is small. However, the higher fuel consumption for EVs allows more welfare change as EV penetration grows. Therefore, the change in total welfare from the EV VMT+gas tax becomes much higher than the gas tax at the optimal rate, approaching the welfare change levels of the other taxes.

3.6. The Best Revenue-Neutral Taxes by Tax Types

3.6.1. The Best Revenue-Neutral Tax Rates. This section presents the applicable tax rates by the corresponding tax types discussed as the second-best optimal taxes. The second-best optimal taxes are much higher than the current gas tax rate. It can be objected to and may be challenging to

[6]Without assuming the initial fuel expenditure value, the welfare change as a proportion of the pre-tax fuel expenditure is described in Appendix 3.B.

apply in practice. Therefore, discussing the politically feasible tax rates may be more interesting, given the tax types discussed in this paper. One of the most plausible cases is to impose a tax that keeps the current government revenue: a revenue-neutral tax. Given the tax types, this section estimates the best revenue-neutral taxes to maximize social welfare.

Table 3.5 shows the best revenue-neutral tax rates by tax type. The current gasoline tax rate is 48 cents/gallon, the base case for calculating the same government revenue. The flat VMT tax is calculated using the fuel economy by constraining the current government revenue. It is 2.2 cents per mile. The burden spreads to two vehicle markets, so the ICE driver is slightly less burdensome, and the EV driver begins to pay the tax for driving. The flat VMT+gas tax is a flat VMT tax to both ICEs and EVs, given some part of the gasoline tax imposed to collect the same revenue. It is calculated numerically with the tax type and the revenue constraints. Instead of lowering the current gas tax, the VMT tax rate is sought as much as possible to improve social welfare. The best revenue-neutral flat VMT+gas tax only requires 0.3 cents/mile for VMT tax to both fuel-type vehicle markets, with 41.8 cents/gallon only for ICEs.

TABLE 3.5. **The Best Revenue-Neutral Tax by Tax Types**

	Gas tax		Flat VMT tax		Flat VMT+gas tax		Differential VMT tax		EV VMT+gas tax	
	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV
Estimated MPG	22.0	102.0	22.0	102.0	22.0	102.0	22.0	102.0	22.0	102.0
MEC (cents/gal)	255.8	1,101.6	241.7	1,101.6	241.7	1,101.6	241.7	1,101.6	255.8	1,101.6
- Fuel pollution	25.0	0.0	25.0	0.0	25.0	0.0	25.0	0.0	25.0	0.0
- Miles component	19.9	183.6	18.7	183.6	18.7	183.6	18.7	183.6	19.9	183.6
- congestoin	140.6	612.0	132.0	612.0	132.0	612.0	132.0	612.0	140.6	612.0
-Accident	70.3	306.0	66.0	306.0	66.0	306.0	66.0	306.0	70.3	306.0
Components of the Tax (cents/gal)	48.0	-	47.5	220.3	47.9	28.5	48.0	0.0	48.0	0.0
- Fuel pollution	4.7	-	4.9	0.0	5.0	0.0	5.0	0.0	4.7	0.0
- Miles component	3.7	-	3.7	36.7	3.7	4.7	3.7	0.0	3.7	0.0
- congestoin	26.4	-	26.0	122.4	26.2	15.8	26.2	0.0	26.4	0.0
-Accident	13.2	-	13.0	61.2	13.1	7.9	13.1	0.0	13.2	0.0
Optimal tax for each tax type										
Gas tax (cents/gal)	48.0	-	-	-	41.8	-	-	-	48.0	-
VMT tax (cents/mile)	-	-	2.2	2.2	0.3	0.3	2.2	0.0	-	0.0
Tax equivalent										
(cents/mile)	(2.2)	-	-	-	(1.9)	-	-	-	(2.2)	-
(cents/gal)	-	-	(47.5)	(220.3)	(6.1)	(28.5)	(48.0)	(0.0)	-	(0.0)

Notes: MEC for EVs is converted in cents/gal using estimated MPG. Components of the tax only incorporate the marginal external cost to be corrected by the tax. The components are calculated by the MEC ratio of each tax.

TABLE 3.6. **Welfare Effects: The Best Revenue-Neutral Taxes**

	Gas tax		Flat VMT tax		Flat VMT+gas Tax		Differential VMT tax		EV VMT+gas tax	
	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV
Gas tax(cents/gallon)	48.0	-	-	-	41.8	-	-	-	48.0	-
VMT tax(cents/mile)	-	-	2.2	2.2	0.3	0.3	2.2	0.0	-	0.0
Welfare change(% of pretax expen)	0.00	0.00	-0.50	1.16	0.01	0.26	-0.46	0.00	0.00	0.00
Pretax expenditure ($bn/year)	281.05	0.45	281.05	0.45	281.05	0.45	281.05	0.45	281.05	0.45
Estimated welfare change ($bn/year)	0.00	0.00	-1.40	0.01	0.02	0.00	-1.29	0.00	0.00	0.00
Total welfare change ($bn/year)	0.00		-1.39		0.02		-1.29		0.00	

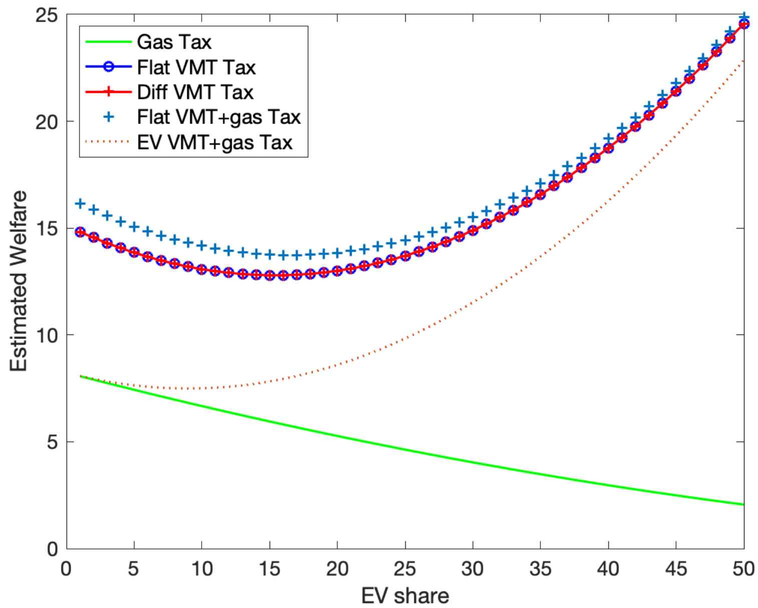
Notes: The pre-tax expenditure of fuel is calculated by multiplying the producer fuel price(q_F) by the total initial fuel consumption(F^0)

The differential VMT tax is 2.2 cents/mile on ICEs and no tax on EVs. These tax rates are also estimated numerically from the tax type and revenue constraint. The best tax set from the model in section 3.4.4 suggests a higher tax for EVs. However, a tiny share of EVs at 1% cannot cover the reduced social welfare from eliminating the gas tax in the ICE market. The revenue constraints cause taxes to deviate from the optimal tax set by imposing the tax only on ICEs. The EV VMT+gas tax is estimated by applying the differential VMT tax on EVs and finding a gas tax rate to maintain government revenue. Same as the differential VMT tax, but using the estimated MPG to convert the tax on ICE to the gas tax rate. With a constantly small EV share, EV VMT+gas tax is the same as the gas tax at 48 cents/gal. Replacing a gas tax with a VMT tax on EVs does not work to improve social welfare with a tiny EV share in the market.

Figure 3.8 and 3.9 show the tax rate changes as EV penetration grows when the government aims to keep the same government revenue. The gas tax is calculated by applying the EV growth rates. Figure 3.8 presents that the gas tax should be raised as EVs grow to collect the same government revenue. However, the flat VMT tax remains regardless of the EV share to collect the same revenue. On the other hand, the flat VMT+gas tax at the best revenue-neutral rate has a larger gas tax share than the VMT tax because the imposition of the VMT tax does not cover the welfare loss resulting from the gas tax cut, given a small share of EVs. As EVs grow, it suggests a significant portion of the VMT tax on both ICEs and EVs to improve welfare. The tax lower bound is zero, so no more gas tax is needed when EVs are enough to offset the welfare loss from a gas tax cut. After the EV share rises above 40%, it eventually approaches the flat VMT tax rate.

Figure 3.9 shows the differential taxes at the best revenue-neutral tax rate. According to section 3.4.4, a higher tax is required for EV than for ICE under the optimal tax set. However, if a gas tax is already levied, the share of EVs should be sufficient to offset the welfare loss caused by replacing the gas tax with the VMT tax. In order to obtain more social benefits with a small share of EVs and government revenue constraints, imposing a VMT tax on ICE alone is preferable to spreading the tax across both vehicles. Therefore, the lower bound of the tax, zero, is imposed on the EV.

FIGURE 3.7. Estimated Total Welfare Change ($bn/year) as EV Share Increases: The Second-Best Optimal taxes



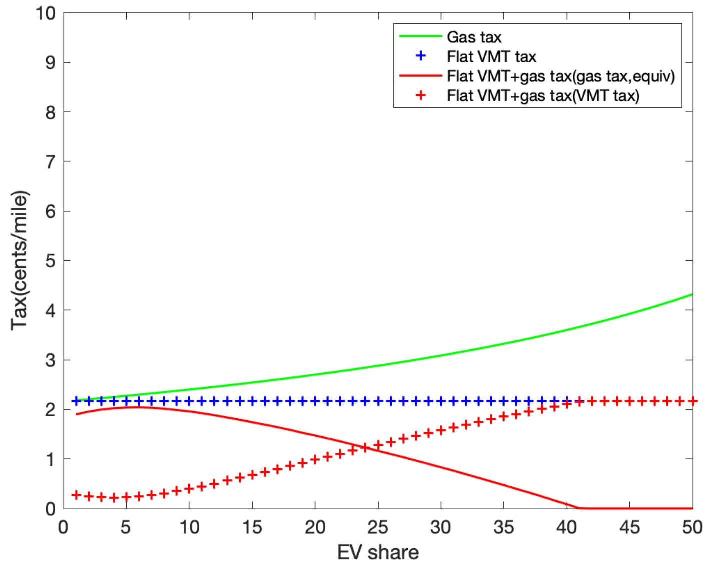
Notes: The estimated total welfare change is the sum of welfare changes in the ICE and EV markets.

However, when a sufficient number of EVs is in the market, the differential VMT tax of the best revenue-neutral taxes approaches the optimal tax set suggested by the model. The EV VMT+gas tax is the same differential VMT tax for EVs and estimates the gas tax on ICE to meet the government revenue restrictions [7]. As a result, the same tax rate as differential VMT tax, excluding tax type.

3.6.2. Welfare Changes of the Best Revenue-Neutral Taxes. This section describes the welfare changes when adopting the best revenue-neutral tax discussed in section 3.6.1. Table 3.6 presents welfare changes for each tax type. Welfare changes will not happen if the government

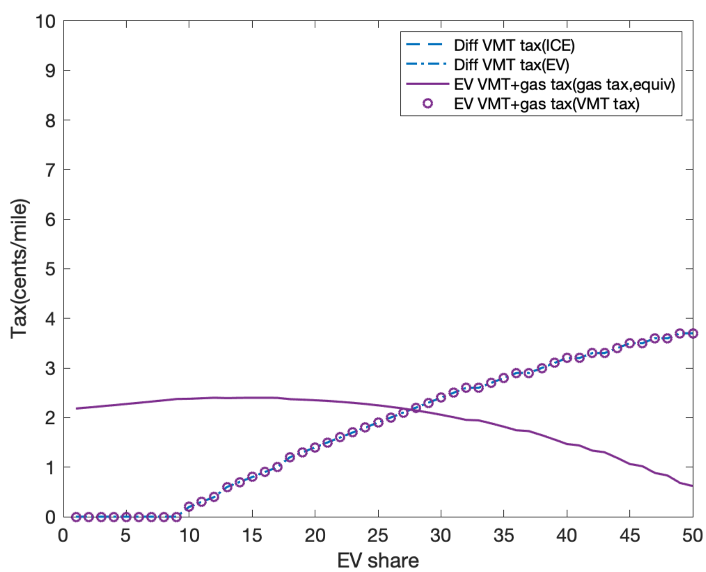
[7]The second-best optimal tax rates are estimated numerically using the model. However, the functional form of the second-best optimal model cannot be applied to the best revenue-neutral taxes due to government tax revenue restrictions. Due to the different tax units of cents/mile and cents/gallon, finding the best revenue-neutral EV VMT+gas tax set over all different EV shares has a significant computational burden. Therefore, the revenue-neutral EV VMT+gas tax is estimated by applying the same VMT tax as the differential VMT tax to EVs and finding the gas tax that satisfies the same government tax revenue. This result is similar to the best revenue-neutral EV VMT+gas tax numerically without any constraints. Also, it makes only a small difference in welfare changes while maintaining consistent results.

FIGURE 3.8. The Best Revenue-Neutral Flat Taxes as EV Share Increases



Notes: The best revenue-neutral taxes are the tax rates under each tax type to maximize welfare with the restriction of the same government revenue with the base case of the current gasoline tax of 48 cents/gallon.

FIGURE 3.9. The Best Revenue-Neutral Differential Taxes as EV Share Increases

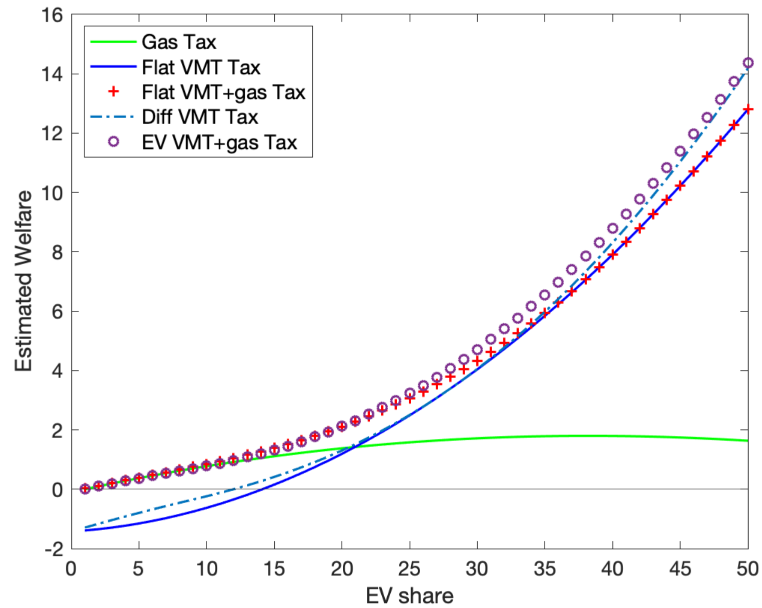


Notes: In the case of government revenue restrictions as described in the text, the EV VMT+gas tax, converted to the same unit of cents/mile, has the same tax rates as the best revenue-neutral differential VMT tax.

maintains the current gas tax. If the government adopts the flat VMT tax or differential VMT tax to maintain the government revenue, the welfare is further deteriorated due to diminishing marginal benefit and the low elasticity ratio with β less than 0.5. Replacing the gas tax with the VMT tax is advantageous only when the welfare of the VMT tax can cover the welfare loss caused by the abolition of the gas tax. However, limited by revenue constraints, the low VMT tax rate cannot cover the loss. Adopting the flat VMT+gas tax would yield positive welfare benefits by taking the initial marginal benefit from the gas tax and converting a portion of the tax into the VMT tax. If not taxed by the VMT tax on ICEs, sufficient EV share needs to offset the welfare loss from lower gas taxes. Therefore, the EV VMT+gas tax at the best revenue-neutral tax rate only needs a gasoline tax for ICEs and no tax for EVs because the proportion of EVs is small. There is no change in welfare in that case.

Figure 3.10 shows the change in gross welfare adopting the best revenue-neutral tax as EV increases. Maintaining the gas tax policy with the same government revenue is only slightly advantageous. There is a limit to increasing the overall welfare because the tax rate for revenue-neutral gasoline tax is much lower than the second-best optimal gas tax rate, and the external costs of driving electric vehicles cannot be addressed. All other revenue-neutral taxes provide welfare benefits but are dependent on EV share. In the early stage of introducing an electric vehicle, the flat VMT+gas tax, capped at current government revenue, provides positive welfare benefits. The EV VMT+gas tax also gives benefits with the flexibility of tax types imposed. However, if there is only a VMT tax type available to be imposed, welfare loss occurs with small EV shares. That is because introducing a low-rate VMT tax cannot offset the loss of eliminating the current gas tax in the ICE market. However, a flat and differential VMT tax will eventually benefit overall welfare when electric vehicles have grown sufficiently. Differential tax types provide more benefits than flat tax types when the revenue is restricted. The EV VMT+gas tax provides the most significant gains under current government revenue constraints, followed by the differential VMT tax. The flat VMT tax and flat VMT+gas tax ultimately provide similar welfare benefits at the same tax rate.

FIGURE 3.10. Estimated Total Welfare Change ($bn/year) as EV Share Increases: The Best Revenue-Neutral Taxes



Notes: The estimated total welfare change is the sum of welfare changes in the ICE and EV markets.

3.7. Conclusion

The gasoline tax has been used to curb externalities but indirectly reduces them by purchasing more efficient vehicles. The VMT tax or the combined tax imposing a tax on miles can improve social welfare by replacing or complementing the current tax policy. This paper presents the theoretical framework and provides three empirical results based on the model. First, the second-best optimal flat and differential VMT tax rates are similar. The parameter for pollution from driving EVs is taken by the literature considering the pollution of battery manufacturing as well as producing electricity. This conservative approach to estimating the pollutants from EVs may overestimate the pollution from driving EVs. However, the environmental benefits of replacing ICEs with EVs are still debated. The analogous external costs for driving ICEs and EVs result in similar rates of differential VMT taxes for each in cents per mile. It is also similar to the flat VMT tax. Suppose electricity or battery manufacturing becomes more environmentally friendly, and the marginal external cost from EV driving is much less than ICE. In that case, at the second-best optimal rate, the differential VMT tax will result in higher social welfare than the flat VMT tax. However, given the current estimated social costs, a flat VMT tax works just as effectively as a differential VMT tax.

Second, the second-best optimal flat VMT+gas tax gives the most significant welfare change among taxes discussed in this paper. The VMT tax provides higher social welfare than the gas tax at the second-best optimal tax rates. However, considering the marginal social benefit, trading the initial benefit from introducing a gas tax for the VMT tax may not be beneficial. That is because fuel demand is more elastic than VMT demand based on the literature. If the ratio is larger than 0.5, the social welfare gain from the VMT tax would be greater than the flat VMT+gas tax. Also, since the model can only find tax rates numerically, finding a gas tax rate that would reap the highest benefit from a flat VMT+gas tax type can be challenging. However, it is worth noting that a flat VMT+gas tax could be an option to improve social welfare, at least as much as adopting a VMT tax.

Finally, as long as the government aims to maintain current government revenues with a small EV share, only a flat VMT+gas tax provides positive welfare benefits. Under the flat tax type, it is advantageous in terms of social welfare to abolish the gas tax only when the share of electric vehicles exceeds 40%. When there is sufficient EV share in the market, among the best revenue-neutral taxes, the EV VMT+gas tax is most favorable, followed by the differential VMT tax. It implies that until there is sufficient EV share in the market, a combined tax type may prevail.

The tax rates described in this paper may differ based on assumptions about parameter values. However, the implications of the results are stringent. A combined tax could be an option to improve social welfare in the early stages of EV adoption. In particular, introducing a VMT tax only for EVs can be more practical and advantageous than the result in this paper, as it can prevent the high cost of retrofitting all vehicles.

Appendix

3.A. Derivation

3.A.1. Deriving the Second-Best Optimal Taxes: Flat Taxes. The maximization problem to derive the second-best optimal tax given each tax type is expressed by the indirect utility function ($V(.)$), using the equations 3.1 - 3.8, as:

$$\mathbf{V} = wV_1 + (1-w)V_2$$

$$V_k = \max_{C,M,F,H} \quad u(C_k, M_k, \pi M_k, H_k, S) - \varphi(P) - \delta(A) \tag{3.25}$$

$$+ \mu_k(M_k(F_k, H_k) - M_k) + \lambda(I_k - C_k - (q_{F_1} + t_{F_k})F_k - q_{H_1}H_k)$$

where μ_k and λ are Lagrange mutipliers. The first-order conditions of partially differentiating equation 3.25 can be expressed:

$$\frac{\partial \mathbf{V}}{\partial t_{F_1}} = -w\lambda F_1 \qquad \frac{\partial \mathbf{V}}{\partial t_{F_2}} = -(1-w)\lambda F_2$$

$$\frac{\partial \mathbf{V}}{\partial P} = -\varphi'(P) \qquad \frac{\partial \mathbf{V}}{\partial A} = -\delta'(A) \qquad \frac{\partial \mathbf{V}}{\partial \pi} = (wM_1 + (1-w)M_2)u_T \equiv \bar{M}u_T \tag{3.26}$$

All derivation has the assumptions that (1) there are two different markets to be charged by each tax, (2) the tax in one market does not directly affect any consumption in the other market, but the total negative externalities impact the utility in both markets and (3) the government budget is constant ($dG = 0$), so the tax rate change in one market affects the tax rate in the other market. Since taxes do not affect market share, the equation 3.10 is not different, but different tax types have different government budget constraints. Also, it uses normative analysis.

Gasoline Tax ($t^*_{F_1}$) When the government imposes a gas tax, the budget constraint is $G = t_{F_1}F_1$. It leads to $dG = dt_{F_1}F_1 + t_{F_1}dF_1 = 0$ by totally differentiating the budget constraint.

Using this condition and the equations 3.24 and 3.26, the second-best optimal gas tax is derived as equation 3.15.

Flat VMT tax (t_v^*) If a flat VMT tax replaces a gas tax, the government budget is $G = \Sigma_{k=1}^{2} w_k t_v M_k$. Total differentiating this equation with holding the government budget constant gives:

$$dG = w(dt_v M_1 + t_v dM_1) + (1-w)(dt_v M_2 + t_v dM_2) \tag{3.27}$$

Also, the corresponding part of the partial differnces for t_v in equation 3.26 is replaced by:

$$\frac{\partial \mathbf{V}}{\partial t_v} = -w\lambda M_1 \qquad \frac{\partial \mathbf{V}}{\partial t_v} = -(1-w)\lambda M_2 \tag{3.28}$$

Also, the following equations need to be considered to use the same notation of marginal external cost:

$$\begin{aligned}
&\frac{dF_k}{dt_v} = \frac{dF_k}{dP_k}\frac{dP_k}{dt_v} = \frac{dF_k}{dP_k}\frac{1}{\alpha_{FM_k}} = \frac{dF_k}{dt_{F_k}}\frac{1}{\alpha_{FM_k}} \\
&\frac{dM_k}{dt_v} = \frac{dM_k}{dP_k}\frac{dP_k}{dt_v} = \frac{dM_k}{dP_k}\frac{1}{\alpha_{FM_k}} = \frac{dM_k}{dt_{F_k}}\frac{1}{\alpha_{FM_k}} \\
&P_k \equiv \begin{cases} q_{f_k} + t_v \frac{1}{\alpha_{FM_k}} & \text{if VMT tax imposed} \\ q_{f_k} + t_{F_k} & \text{if gas tax imposed} \end{cases}
\end{aligned} \tag{3.29}$$

The equation 3.16 is derived by using equation 3.24 - 3.29, and assuming that a representative agent in each market has the same VMT elasticity and miles driven on average as:

$$\eta_{MF_1} = \eta_{MF_2}$$
(3.30)
$$\bar{M}_1 = \bar{M}_2$$

Flat VMT+gas Tax (t_c^*) The flat VMT+gas tax has $G = w(t_c M_1 + t_g F_1) + (1-w)t_c M_2$ as the government budget constraint. Given the same assumptions to derive a flat VMT tax, the equation 3.18 can be derived.

3.A.2. Deriving the Second-Best Optimal Taxes: Differential Taxes. The taxes in the section 3.2.3 also use the same indirect utility function but different government budget constraints.

Differential VMT tax ($t_{vd_k}^*$) If the government introduces the differential VMT tax on each fuel type vehicle, the government budget is $G = \Sigma_{k=1}^{2} w_k t_{F_k} F_k$. Total differentiating this equation with holding the government budget constant gives:

(3.31)
$$\begin{aligned}
&dG = w(dt_{F_1}F_1 + t_{F_1}dF_1) + (1-w)(dt_{F_2}F_2 + t_{F_2}dF_2) + dw(t_{F_1}F_1) - dw(t_{F_2}F_2) \\
&\frac{dt_{F_1}}{dt_{F_2}} = -\frac{w}{(1-w)F_2}(F_1 + t_{F_1}\frac{dF_1}{dt_{F_1}}) - \frac{t_{F_2}}{F_2}\frac{dF_2}{dt_{F_1}} \\
&\qquad = -\frac{w}{(1-w)F_2}(F_1 - t_{F_1}F_{11}) + \frac{t_{F_2}}{F_2}F_{22}\frac{dt_{F_2}}{dt_{F_1}} \\
&\frac{dt_{F_1}}{dt_{F_2}} = -\frac{w}{(1-w)}\frac{F_1 - t_{F_1}F_{11}}{F_2 - t_{F_2}F_{22}}
\end{aligned}$$

By plugging in these equations, the first-order condition of totally differentiating the indirect utility function with respect to each tax can be simplified to the equation 3.19. Then, the optimal set of VMT taxes in both markets can be derived as the equation 3.20.

3.A.3. Welfare Change. This section illustrates the equation 3.22 and 3.23. The optimal tax set is the equation 3.20. Using the notations of $t^*_{F_k}$ and η_{FF_k}, the differentiated indirect utility function can be expressed as:

$$\frac{d\mathbf{V}}{dt_k} = \lambda w_k \eta_{FF_k} \frac{F_k}{P_k}(t^*_k - t_k) \tag{3.32}$$

By the assumption of a constant-elasticity, the fuel consumption is as:

$$F_k = F^0_k(\frac{P_k}{P^0_k})^{-\eta_{FF_k}} \tag{3.33}$$

The equation 3.32 and 3.33 lead to the equation 3.22 and 3.23.

3.B. Welfare Change as a Proportion

3.B.1. The Second-Best Optimal Taxes. The welfare change as a proportion of the pre-tax fuel expenditure is convenient for understanding the optimal tax effects regardless of the initial fuel consumption. Figure 3.B.1 shows the change of the social welfare portion of the initial fuel expenditure in the ICE market when adopting the second-best optimal taxes as EV share grows up to 50% on the road. As the ICE market share decreases, the tax impact on overall welfare decreases, so the effect of proportional welfare change decreases for all tax types. The lower rates of the optimal gas tax lead to lower welfare changes, and the welfare benefits decrease as the ICE share is reduced. The welfare effects of the taxes corporating VMT tax types, such as flat and differential VMT taxes, are similar because the tax rates are similar. The flat VMT+gas tax reaps more benefits by finding a gas tax rate that can obtain more benefits than the VMT tax at the beginning of the tax introduction. These welfare gains are almost twice the benefits of adopting the second-best optimal gas tax. Of the EV VMT+gas tax, the gas tax on ICE is the second-best optimal gas tax, so the welfare change is the same as the gas tax welfare change in the ICE market.

FIGURE 3.B.1. Welfare Change in % of the Fuel Expenditure as EV Share Increases: The Second-Best Optimal Taxes of ICEs

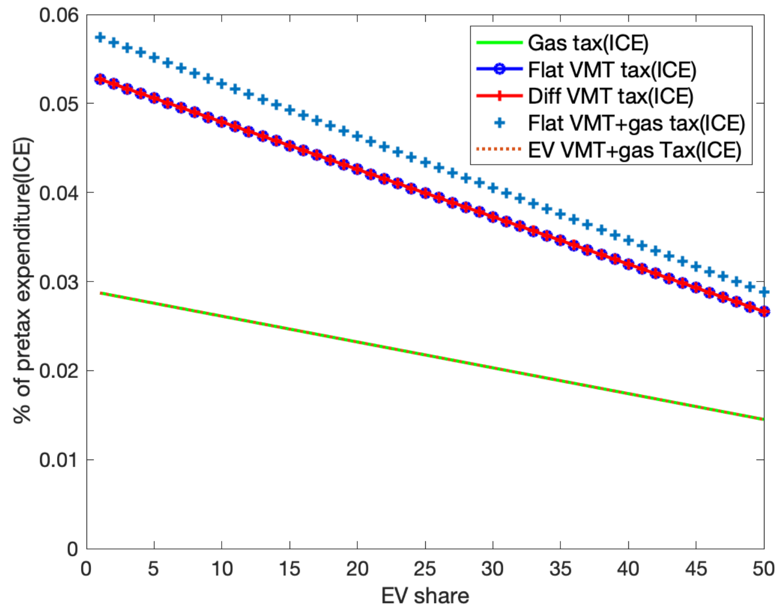
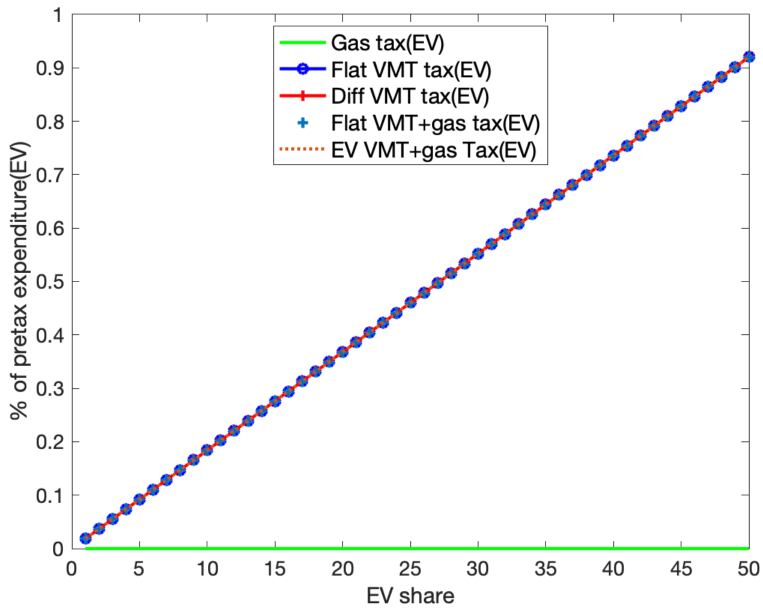


Figure 3.B.2 presents the social welfare change portion of the initial fuel expenditure in EV markets from introducing the second-best optimal tax rates as EVs grow. Since all taxes imposed on EVs are newly introduced, the proportion of welfare changes is much higher than that of ICE. Since there is no tax on EVs under the gas tax, no welfare change is generated in EV markets. On the other hand, the VMT and combined taxes for EVs have an analogous change in welfare as the portion of the fuel expenditure, regardless of the specific tax types. That is because the tax rates under these types are very similar, given that the external costs between ICEs and EVs are not significantly different and the imposed gas tax of the flat VMT+gas tax is comparably small.

3.B.2. The Best Renevue-Neutral Taxes. Figure 3.B.3 shows the change in the social welfare portion of the initial fuel expenditure in the ICE market when adopting the best revenue-neutral taxes as EVs grow. If the revenue is capped, the gas tax will need to rise as EVs grow. Increasing gas tax rates gradually increase social welfare. The flat VMT tax remains constant regardless of EV shares, but the welfare loss from adopting the flat VMT tax decreases. That is because the

FIGURE 3.B.2. Welfare Change in % of the Fuel Expenditure as EV Share Increases: The Second-Best Optimal Taxes of EV



effect of the tax on overall welfare decreases as the share of ICE decreases. The flat VMT+gas tax, differential VMT tax, and EV VMT+gas tax have similar welfare change paths but different levels. The abolition of the existing gas tax causes a loss of welfare. Therefore, the differential VMT tax, which should eliminate the gasoline tax, has the most severe welfare change. On the other hand, the flat VMT+gas tax and EV VMT+gas tax provide positive welfare changes by keeping a gas tax. In the early stage of introducing EVs, all these tax types have a higher tax on ICEs with a small share of EVs. That is because it needs the highest VMT tax rate to cover the welfare loss from cutting the gas tax in ICE market. As the share of EVs increases, introducing a VMT tax on EVs gives more welfare gains. It reduces the tax required for ICE and, in turn, reduces welfare.

Figure 3.B.4 presents the social welfare change portion of the initial fuel expenditure in EV markets when adopting the best revenue-neutral taxes by different EV shares. Since the gas tax policy applies only to ICE, it does not affect the welfare of the electric vehicle market. However, in all other tax types, there are positive welfare changes for the EV market due to the newly introduced

tax. The flat VMT tax rate is constant, so the welfare change only depends on the EV share effects on the overall welfare change. The flat VMT+gas tax gradually increases the benefits. If a sufficient number of EV shares trigger the abolition of the gas tax and the tax rate approaches the flat VMT tax, the welfare change will also equal the welfare of the flat VMT tax. The differential VMT tax and the EV VMT+gas tax provide the same welfare changes at the same tax rate. In the early stage of EV introduction, there is no need to tax EVs, so there is no welfare change. However, it provides the most significant welfare benefit as EVs grow.

FIGURE 3.B.3. Welfare Change in % of the Fuel Expenditure as EV Share Increases: The Best Revenue-Neutral Taxes of ICE

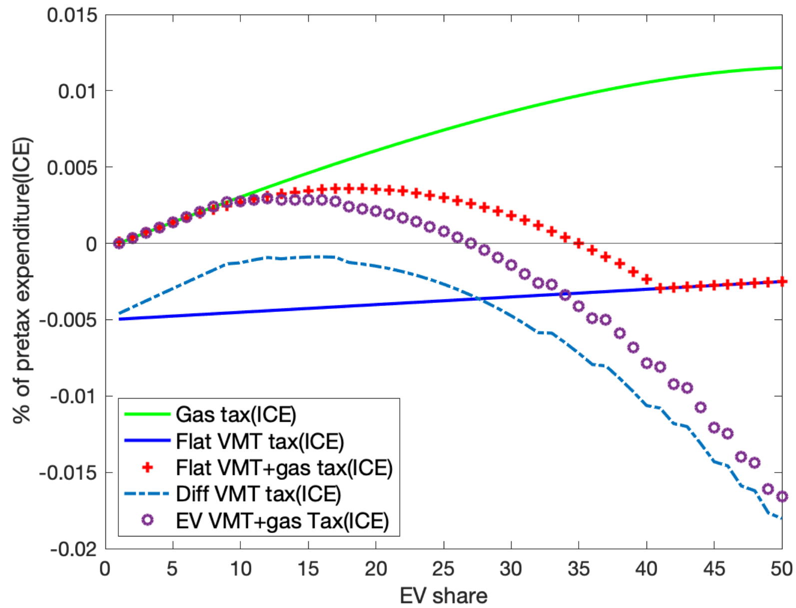
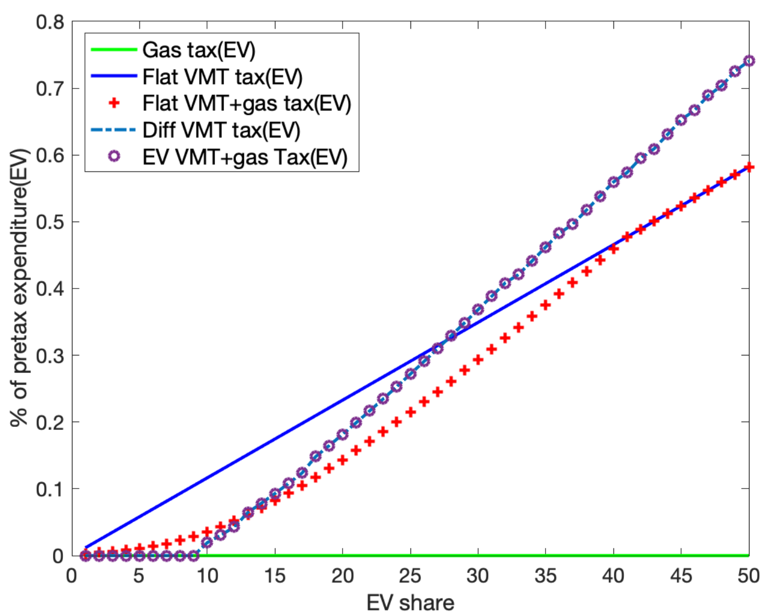


FIGURE 3.B.4. Welfare Change in % of the Fuel Expenditure as EV Share Increases: The Best Revenue-Neutral Taxes of EV



Bibliography

Alberini, A., Burra, L. T., Cirillo, C., and Shen, C. (2021). Counting vehicle miles traveled: What can we learn from the nhts? *Transportation research part D: transport and environment*, 98:102984.

Anderson, S. T., Kellogg, R., and Sallee, J. M. (2013). What do consumers believe about future gasoline prices? *Journal of Environmental Economics and Management*, 66(3):383–403.

Bento, A. M., Goulder, L. H., Jacobsen, M. R., and Von Haefen, R. H. (2009). Distributional and efficiency impacts of increased us gasoline taxes. 99(3):667–99.

Bjertnæs, G. H. (2019). Efficient combination of taxes on fuel and vehicles. *The Energy Journal*, 40(The New Era of Energy Transition).

Cheon, J. (2022). *Distributional Effects of A Vehicle Miles Traveled Tax over the Different Vehicle Efficiency*. PhD thesis, Agricultural and Resource Economics, University of California, Davis.

Coyle, D., Robinson, F., Zhao, Z., Munnich, L., and Lari, A. (2011). From fuel taxes to mileage-based user fees: rationale, technology, and transitional issues.

Davis, L. W. and Sallee, J. M. (2020). Should electric vehicle drivers pay a mileage tax? *Environmental and Energy Policy and the Economy*, 1(1):65–94.

Dimitropoulos, A., Oueslati, W., and Sintek, C. (2018). The rebound effect in road transport: A meta-analysis of empirical studies. *Energy Economics*, 75:163–179.

Dubin, J. A. and McFadden, D. L. (1984). An econometric analysis of residential electric appliance holdings and consumption. *Econometrica: Journal of the Econometric Society*, pages 345–362.

Duncan, D., Nadella, V., Giroux, S., Bowers, A., and Graham, J. D. (2017). The road mileage user-fee: Level, intensity, and predictors of public support. *Transport Policy*, 53:70–78.

Feng, Y., Fullerton, D., and Gan, L. (2013). Vehicle choices, miles driven, and pollution policies. *Journal of Regulatory Economics*, 44(1):4–29.

Gillingham, K. (2011). How do consumers respond to gasoline price shocks? heterogeneity in vehicle choice and driving behavior. *Manuscript: Yale University*.

Gillingham, K. and Munk-Nielsen, A. (2019). A tale of two tails: Commuting and the fuel price response in driving. *Journal of Urban Economics*, 109:27–40.

Goetzke, F. and Vance, C. (2021). An increasing gasoline price elasticity in the united states? *Energy Economics*, 95:104982.

Goldberg, P. K. (1998). The effects of the corporate average fuel efficiency standards in the us. *The Journal of Industrial Economics*, 46(1):1–33.

Goldstein, S. (2014). *Implementing a Vehicle Miles Traveled (VMT) Tax*. PhD thesis, Johns Hopkins University.

Holland, S. P., Mansur, E. T., Muller, N. Z., and Yates, A. J. (2016). Are there environmental benefits from driving electric vehicles? the importance of local factors. *American Economic Review*, 106(12):3700–3729.

Hymel, K. M. and Small, K. A. (2015). The rebound effect for automobile travel: asymmetric response to price changes and novel features of the 2000s. *Energy Economics*, 49:93–103.

Jacobsen, M. R. (2013). Evaluating us fuel economy standards in a model with producer and household heterogeneity. *American Economic Journal: Economic Policy*, 5(2):148–87.

Kleit, A. N. (2004). Impacts of long-range increases in the fuel economy (cafe) standard. *Economic Inquiry*, 42(2):279–294.

Knittel, C. R. and Sandler, R. (2018). The welfare impact of second-best uniform-pigouvian taxation: evidence from transportation. *American Economic Journal: Economic Policy*, 10(4):211–42.

Langer, A., Maheshri, V., and Winston, C. (2017). From gallons to miles: A disaggregate analysis of automobile travel and externality taxes. *Journal of public Economics*, 152:34–46.

Levin, L., Lewis, M. S., and Wolak, F. A. (2017). High frequency evidence on the demand for gasoline. *American Economic Journal: Economic Policy*, 9(3):314–47.

Li, S., Linn, J., and Muehlegger, E. (2014). Gasoline taxes and consumer behavior. *American Economic Journal: Economic Policy*, 6(4):302–42.

Lin, C.-Y. C. and Prince, L. (2009). The optimal gas tax for california. *Energy Policy*, 37(12):5173–5183.

Linn, J. (2016). The rebound effect for passenger vehicles. *The Energy Journal*, 37(2).

Liu, W. (2015). Gasoline taxes or efficiency standards? a heterogeneous household demand analysis. *Energy Policy*, 80:54–64.

Marion, J. and Muehlegger, E. (2011). Fuel tax incidence and supply conditions. *Journal of public economics*, 95(9-10):1202–1212.

McMullen, B. S., Zhang, L., and Nakahara, K. (2010). Distributional impacts of changing from a gasoline tax to a vehicle-mile tax for light vehicles: A case study of oregon. *Transport Policy*, 17(6):359–366.

Metcalf, G. E. et al. (2022). The distributional impacts of a vmt-gas tax swap. *NBER Chapters*.

Mitropoulos, L. K., Prevedouros, P. D., and Kopelias, P. (2017). Total cost of ownership and externalities of conventional, hybrid and electric vehicle. *Transportation research procedia*, 24:267–274.

Parry, I. W. and Small, K. A. (2005). Does britain or the united states have the right gasoline tax? *American Economic Review*, 95(4):1276–1289.

Small, K. A. and Rosen, H. S. (1981). Applied welfare economics with discrete choice models. *Econometrica: Journal of the Econometric Society*, pages 105–130.

Small, K. A. and Van Dender, K. (2007). Fuel efficiency and motor vehicle travel: the declining rebound effect. *The Energy Journal*, 28(1).

Spiller, E. (2012). Household vehicle bundle choice and gasoline demand: A discrete-continuous approach. Technical report.

Su, Q. (2015). How does fuel economy of vehicles affect urban motor vehicle travel in the usa? *Energy Efficiency*, 8(2):339–351.

Tong, F. and Azevedo, I. M. (2020). What are the best combinations of fuel-vehicle technologies to mitigate climate change and air pollution effects across the united states? *Environmental Research Letters*, 15(7):074046.

Weatherford, B. A. (2012). *Mileage-based user fee winners and losers: An analysis of the distributional implications of taxing vehicle miles traveled, with projections, 2010–2030*. PhD thesis, The Pardee RAND Graduate School.

West, S. E. (2004). Distributional effects of alternative vehicle pollution control policies. *Journal of public Economics*, 88(3-4):735–757.

Xing, J., Leard, B., and Li, S. (2019). What does an electric vehicle replace? Technical report, National Bureau of Economic Research.