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Going Beyond the Blend Wall: Policy Incentives for Fuel Consumers to Supplement the Renewable Fuel Standard

Jia Zhong, Madhu Khanna, and Xiaoguang Chen

Abstract: The direct incentive from the renewable fuel standard for fuel consumers is limited while the penetration of flexible fuel vehicles (FFV) stays stagnated. To study alternative policy incentives and its mechanism targeted at consumer to supplement the standards from the demand side, we develop a framework of dynamic economic partial equilibrium model. We find that under RFS 2022 schedule, explicitly pronounced cross-subsidization on both fuels (yearly average $0.41/gge tax on preblended fuel and $2.35/gge subsidy on ethanol) and vehicles (average $2.8k tax on CV and $2.4k purchase subsidy on FFV) are needed for consumers to switch to higher ethanol blends and FFV. The retail E100 is priced lower than its energy content as with E10 to the extent to attract FFV users consume higher blends and stimulate FFV purchase while offset the drawbacks of the higher vehicle costs and its less fuel efficiency. A lengthened policy not only alleviates the pricing strategies pressure but also reduces the welfare loss. Improved competitiveness in sales price is more effective in benefiting the vehicle drivers with less feebate intensity.

Keywords: Consumer incentives, Renewable fuel standard, Flexible fuel vehicle, Dynamic optimization, Social welfare

1 Introduction

The Renewable Fuel Standard (RFS) is a federal program established by the Energy Independence and Security Act in 2010 to reduce reliance on transport-based imported oil, mitigate greenhouse gas emissions, and enhance rural development. With this Act, the Environmental Protection Agency (EPA) prescribes an increasing annual volumetric target for ethanol to be blended to 35 billion gallons by 2022. [1] The RFS standard credits the producers and

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[1] Though biomass-based biodiesel is also nested in the advanced biofuel requirement, the quantity mandated and produced is limited around 2 billion gallon that is not the focus of this study.

blenders with tradable Renewable Identification Number (RIN) as incentive, but the pass-through effect of the RIN price subsidy to retail E85 price is limited for various reasons including information lag (Knittel et al., 2015).[2] Thus, the standard does not provide direct incentives for fuel consumers to either switch to higher blends or to diverts to alternative flex-fuel vehicles (FFVs) that run on any ethanol blends up to E100. FFVs can also overcome the technical inability of the conventional vehicle (CV), which cannot run on the preblended fuel with more than E10 due to the engine tolerability to alcohol.[3] The near absence of the incentives for FFVs restrict the ability to consume the mandated goal of ethanol, which will likely stymy the RFS policy along with modification of lowering mandate in both the quantity and the blend rate since 2013 (EIA, 2009 and 2014).

However, FFVs market penetration in the US is limited in recent years with only 7.6% of the light-duty vehicle fleet and 18.36 million in 2015 (EIA, 2015). The lapse of FFV penetration has many reasons: First, the pricings of alternative fuel blends are higher relative to gasoline on an energy equivalent basis (DOE, 2017a). Second, even if the pricing is equivalent on energy content, the FFV motorists significantly discount E85 compared to E10 mainly because of the subjective observation of posted price, the prominence of price difference, and habit routine (Liao and Pouliot, 2016). Moreover, the inadequate fueling stations is not enough to supply the higher ethanol blends (Babcock, 2013; Tyner et al., 2011). But as the manufacturer’s outfit cost of FFV become minimal at $100-$200 (Anderson and Sallee, 2011) and the fuel economy on energy equivalent basis of FFV are approaching that of CV (National Research Council, 2015), improvements in FFV specification also attract attention with higher market competitiveness.

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[2] "E" followed by numbers describes ethanol blended as percentage of the total fuel by volume.

[3] In early periods of the RFS, the preblended fuel has an ethanol blend less than 10%. Now preblended fuel approaches E10 blend wall due to the fuel accessibility and CV specification.

To understand the economic motivations for the US drivers towards higher ethanol blends and switch to FFV to supplement the RFS mandate going beyond the blend wall, it is important to examine the mechanism of policy incentives from the demand side to achieve the RFS. This study addresses the following research objectives: (1) to analyze the combination of policy incentives to achieve higher level of alternative blends and wider adoption of alternative vehicles; (2) to study the optimal pathway of the FFV adoption and vehicle fleet composition; (3) to estimate the welfare effect of RFS compliance; (4) and to study several potential policy designs under the current tendency, which might have: greater competitiveness of FFV in sales price and fuel economy, and slower speeds of mandate realization.

We first develop a dynamic partial equilibrium model to examine the policy incentives for consumers and producers and investigate the optimal pricing of alternative fuel blends (preblended fuel or E100) and vehicles (CV or FFV) to achieve the mandate. Using a welfare-economic framework, we numerically simulate the implicit taxes and subsidies on the alternative fuels, and the timing and extent to which the existing vehicles need new FFVs. The social welfare effects of RFS interventions are also explored with their distributional implications for vehicle-mile-traveled (VMT) consumers, vehicle purchasers, and fuel producers.

Moreover, we consider the foreseeable progresses in the FFV specifications and run three other scenarios with improved specification of FFV with (1) identical initial purchase compared to CV, (2) identical fuel economy compared to CV, (3) composite improvement with both identical initial cost and fuel economy compared to CV.

Finally,we also take the ebbing strength of the mandate into consideration and carry out three scenario analyses to explore the impact of the policy stringency on the transportation sector. The RFS of three timelines to reach quantity goal at 2022, 2030, and 2040 are therefore simulated based on EIA projections. The welfare effectiveness of regulator flexibility in RFS and vehicle fleet composition with the different RFS pathways reset are therefore studied.

The main results we find in this study are that under RFS 2022 schedule, explicitly pronounced cross-subsidization on both fuels (yearly average \$0.41/gge tax on preblended fuel and \$2.35/gge subsidy on ethanol) and vehicles (average \$2.8k tax on CV and \$2.4k purchase subsidy on FFV). The retail E100 is priced lower than its energy content as with E10 to the extent to attract FFV users consume higher blends and stimulate FFV purchase while offset the drawbacks of the higher vehicle costs and its less fuel efficiency. A lengthened policy alleviates the pricing strategies pressure and also reduces the welfare loss. Improved competitiveness in sales price is more effective in benefiting the vehicle drivers with less feebate intensity.

2 Literature Review

Several studies have examined the market effects and welfare outcomes with other alternative biofuel policy instruments to RFS. Interventions of ethanol subsidies and fuel taxes are found as second best to tariff restrictions and have a net gain in social welfare (Cui et al., 2011; Lapan and Moschini, 2012). The study of de Gorter and Just, (2009a) shows the large deadweight costs of biofuel tax credits that dwarf the triangular deadweight loss of traditional farm subsidies. The blend mandate implemented alongside fuel tax would achieve high ethanol consumption (Cui et al., 2011). These static analyses only focus on the supply side of fuel sectors with only gasoline and ethanol as fuel choices, and assume ethanol blend is no greater than 10%. Many studies also outline some suggestive RFS reforms aimed at reducing uncertainty of policy implementation via cost containment (Lade et al., 2016a), rate mandate (Lade et al., 2016b; Smith, 2016), multiyear time frame or at less frequent time interval for rulemaking (Smith, 2016; Stock, 2015). However, to our knowledge, these researches have not considered the policies needed to induce the sufficient demand from market to achieve an overall quantity mandate.

The driving demand is widely studied in the literature using simulation models that also integrated with the fuel choice decisions in compliance with RFS. Some studies use the partial equilibrium model under welfare economic framework to analyze the environmental impact and market effect on VMT driving behaviors among alternative vehicles including FFV (Chen et al., 2014; Nuñez and Önal, 2016). However, neither do the above models consider vehicle fleet dynamics nor include the vehicle choices or their purchase costs. The study by Vimmerstedt et al (2012) modeled vehicle demand in response to the policy incentives for ethanol and incorporated it within the biofuel supply chain model. However, the interactions of fuel choice are absent. For the all above studies, the assumptions that all consumers own FFVs and can shift their vehicle choice without any economic cost are problematic. A general equilibrium model was set up by Bunch et al. (2015), jointly considering both vehicle and fuel choices including vehicle cost, vehicle attribute, refueling infrastructure, and individual preference. However, the VMT consumption is exogenously determined and the integrated model functioned as a “black box” without knowing much about the policy mechanism.

The estimations of FFVs stock, needed by consumer in particular, vary widely between different sources related to the response of the uncertainties about both the expectation of the ethanol production and regulatory mandate. ORNL estimates the recent FFV use operating on E85 is only 862 thousand by 2011 (Davis et al., 2015), which is 40 % of the total FFV stock. The rest 60% of the FFV fleet using primarily gasoline, as in many cases FFV owners are unaware of the flex-fueling capacity. Under different pathways of the RFS agenda considering conditions of the raised blend limit of E15, thermochemical refining, and a waiver on cellulosic ethanol, Tyner’s FFV stock estimation varies from 8.48 to 121.53 million by 2022 (Tyner et al., 2011).

As the ethanol consumption recently projected falls short of the mandate dwindling to around 15 B gallon by 2050 (EIA, 2017), the estimation of FFV stock also drops from 59 million in 2035 (EIA, 2010) to less than 33 million before 2050 (EIA, 2017). However, without discussing the interactive fuel choices of the FFV owners, the RFS compliance mechanism behind these estimations is unclear.

This paper extends the previous studies by considering the costs of structural changes in vehicle fleet and allowing the vehicle fleets dynamics with early retirement and age distribution while having a new fuel choice sets of preblended fuel and E100. By performing a normative policy analysis, this paper fills in the literature gap about the policy implications needed to induce a shift towards renewable fuels and FFVs to comply with RFS.

3 Stylized Model

Our theoretical model builds on the social welfare analytical framework from Khanna et al. (2016) and is further developed under the RFS policy context in the US. Market equilibrium is achieved by maximizing the sum of consumers' and producers' surpluses in multiple markets subject to various technological, fuel availability and policy constraints. For simplicity, we assume perfectly competitive markets of VMTs, ethanol, and gasoline, taking all vehicle drivers as price takers of VMT and fuel prices and have perfect information about the policy incentives. Fuel producers are assumed free to enter or exit the market. For simplicity, ethanol fuel stations and vehicle choice are assumed widely accessible nationwide. A graphical model providing the details of these markets is displayed in Figure 1. For convenience, we use the upper case to denote the decision variables, the subscripts for the generic indexes, the superscripts as the set indexes, and Greek letters for parameters. Notation details are listed in Appendix B.

We assume that the total national VMT produced by FFVs and CVs are identical. This aggregated VMT (denoted as M in Figure 1a) from the two submarkets by vehicle types (M^{CV} and M^{FFV} in Figure 1b and c) follows a linear downward-sloping inverse demand function. In the absence of any government intervention in the fuel and vehicle markets, the market equilibrium mileage consumption (M^0 for national total and vehicle-specific consumption M^{CV0} and M^{FFV0}). [4]

The VMT driven is produced by two vehicles combusting different fuels. With current 95% of the gasoline sold in the US blended with 10% ethanol as E10 (EIA, 2016), this paper focuses on the fuel markets choice of preblended fuel E10 and E100 that enable the blends to go beyond the blend wall. The preblended fuel market is a composite of the preblended ethanol and gasoline with blend rate of κ (E10 has a κ of 10%). The supply curve of the preblended fuel is integrated as $S^b(B) = (1- \kappa)S^g(G) + \kappa\, S^e(E)$ by blending gasoline and ethanol at blend rate κ. Besides the domestic fuel supply (denoted as n), the US also has a net import gasoline supply from the rest of the world (denoted as r), as shown in Figure 1g. Total ethanol consumption (TE in Figure 1f) is the sum of ethanol preblended (E in Figure 1d) and E100 (H in Figure 1e). The baseline total ethanol TE^0 is composed of preblended ethanol at E^0 and low level of E100 at H^0 with ethanol blend rate close to 3.5%, whereas the initial preblended gasoline is high at G^0.

In general, the endogenously determined variables of this partial equilibrium model include vehicle-specific VMT and fuel consumptions, and also the associated vehicle dynamics. Fuel choices are distinct that CV drivers decide how much preblended fuel (B) to consume and FFV drivers need to select between preblended fuel (B) and E100 (H). Vehicle decisions of new vehicles inputs (N), early-retired vehicles (R), and the corresponding vehicle stock (V) are used for VMT production (M).

To find the optimal level of above decision variables, the objective is to maximize the present

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[4] The market equilibria of business-as-usual scenario are denoted with 0 in the superscript for variables.

value of social welfare over a planning horizon of T. As Figure 1 shows, we calculate the social surplus by subtracting the total cost (area below the inverse supply curve) from the total benefit (area below the inverse demand curve). We then subtract other vehicle purchase costs and the operational and management (O&M) cost. Using the discounted present value accruing over the study periods until the end of T with a discount factor of ρ, the model provides a forward-looking projection of the transportation sector.

$$\begin{aligned} &max \sum_t \rho^{t\text{-}1}[\int D^{\mathrm{m}}(\cdot)\mathrm{d}(\cdot) - \int \mathrm{S}^{\mathrm{g,r}}(\cdot)\mathrm{d}(\cdot) + \int \mathrm{S}^{\mathrm{g,n}}(\cdot)\mathrm{d}(\cdot) - \int \mathrm{S}^{e}(\cdot)\mathrm{d}(\cdot) \\ &-\sum_i \varphi_i N_t^i - \eta \sum_{i,a} M_{a,t}^i - \varepsilon \sum_a V_{a,t}^i] + \rho^T \beta \sum_{i,a} \varphi^i \pi_a V_{a,t}^i \end{aligned} \tag{1}$$

Equation 1 displays the objective function of maximizing the net present value of the total social welfare. The first integral in the first line represents the area under the inverse demand functions of total VMT by both CV and FFV and described the total benefit of driving VMT (shaded area in Figure 1a). The next three integrals in the first line are the area under the inverse supply function of the total gasoline supply from both net imported and domestic production, and total ethanol supply (Figure 1g and f). The next three terms in the second line are the total cost of new vehicle purchase (*φ* as purchase price per vehicle), the O&M cost (η as per mile cost), and vehicle registration (ε per year per vehicle).

Even though some of these vehicles are drivable not reaching the extreme of the vehicle life (age 24) by the end of the simulation period *T*, we take into account their depreciated vehicle value remained without considering any further driving behavior.[5] By selling the auto parts to the dealer, recycling center, or sending the vehicle to the auto parts auction, the driver could recover the scrappage value showed in last term of equation 1 in year *T*. The coefficient *β* represents the vehicle market value loss once the vehicle is sold newly by the vehicle dealer

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[5] For purpose of setting up the age property of vehicle fleet, we use the full range of the vehicle age up to age 24 that is observed from the National Household Transportation Survey.

(80% in this study). Further depreciation π_a is relevant to the aging problems after *a* years of wear and tear.

We use the following constraints to define the market equilibrium, the policy mandate, and the vehicle's equation of motion.

$$\sum_{\mathrm{a}} M_{\mathrm{a,t}}^{CV} / \gamma_{\mathrm{a,t}}^{CV} = \xi \times B_{\mathrm{t}}^{CV} \quad \forall \mathrm{t} \qquad \lambda_{\mathrm{t}}^{1,CV} \tag{2.1}$$

$$\sum_{\mathrm{a}} M_{\mathrm{a,t}}^{FFV} / \gamma_{\mathrm{a,t}}^{FFV} = \xi \times B_{\mathrm{t}}^{FFV} + \frac{2}{3} H_{\mathrm{t}} \quad \forall \mathrm{t} \qquad \lambda_{\mathrm{t}}^{\mathrm{1,FFV}} \tag{2.2}$$

$$V_{i,a,t} \times \varsigma_a \geq M_{i,a,t} \quad \forall i,\mathrm{a,t} \qquad \lambda_{\mathrm{a,t}}^{\mathrm{2,i}} \tag{3}$$

$$\kappa_t (B_t^{CV} + B_t^{FFV}) + H_t \leq E_t^s \quad \forall \mathrm{t} \qquad \lambda_{\mathrm{t}}^{\mathrm{3E}} \tag{4.1}$$

$$(1-\kappa)(B_t^{CV} + B_t^{FFV}) \leq G_t^{\mathrm{n},s} + G_t^{r,s} \quad \forall \mathrm{t} \qquad \lambda_{\mathrm{t}}^{\mathrm{3G}} \tag{4.2}$$

$$\kappa_t \sum_i B_t^i + H_t \geq \theta_t (\sum_i B_t^i + H_t) \quad \forall \mathrm{t} \qquad \lambda_{\mathrm{t}}^{4} \tag{5}$$

$$N_{t\,i,t}^i = V_{a1,t}^i \quad \forall i,\mathrm{t} \qquad \lambda_{\mathrm{t}}^{\mathrm{5\_1,i}} \tag{6.1}$$

$$V_{a,t}^i = V_{a-1,t-1}^i - R_{a-1,t-1}^i \quad \forall i, a24 \geq a \geq a2, T \geq t \geq t2 \qquad \lambda_{\mathrm{a,t}}^{\mathrm{5\_2,i}} \tag{6.2}$$

$$V_{a,t1}^i = v_{a-1}^{0,i} - R_{a-1,t1}^i \quad \forall i, \mathrm{a} \geq \mathrm{a2, t=t1} \qquad \lambda_{\mathrm{a}}^{\mathrm{5\_3,i}} \tag{6.3}$$

The VMT markets are described from equation 2 to equation 3. Equation 2.1 described the sum of CV fuel demand over each age group *a* in year *t* from the VMT demand ($M_{\mathrm{a,t}}^{CV}$) divided by its fuel efficiency ($\gamma_{\mathrm{a,t}}^{CV}$) should be met by the supply of preblended fuel B_{t}^{CV} at an energy equivalent basis with coefficient of ξ.[6] Note that the fuel efficiency of new vehicle increases over time that it vary by age. Similarly in year *t*, equation 2.2 defines the energy equivalent base of total supply for the preblended fuel (B_{t}^{FFV}) and E100 (H_{t}) meets the total FFV demand for miles ($M_{\mathrm{a,t}}^{FFV}$) across age groups divided by its fuel efficiency ($\gamma_{\mathrm{a,t}}^{FFV}$). Meanwhile, the VMT driving capacities of the vehicle fleet of age *a* in year *t* is confined by ς_a (exogenous parameters

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[6] Per gallon ethanol provides two-thirds energy of the per gallon gasoline. Similarly, per gallon of preblended fuel with blends less than 10% provides ξ energy of the per gallon gasoline. ξ =0.967

in miles per vehicle) in equation 3, given its vehicle stock ($V^{i}_{a,t}$).

Fuel market equilibrium of ethanol and gasoline are described below. Equation 4.1 establishes the demand and supply balance of ethanol. The total demand on the left-hand side, including preblended ethanol (with blend rate of κ) plus the E100 (*H*) in year t, should be met by the domestic ethanol supply on the right. Similarly, a balance for the gasoline market is specified in equation 4.2. The domestic gasoline demand on the left-hand side in the form of preblended fuel (with 1-κ by volume) can be met by domestic and imported supply of gasoline on the right-hand side in year t.

The RFS blend rate mandate in equation 5 requires total ethanol consumption by CVs and FFVs in the US in the form of either E100 (*H*) or preblended ethanol, to be at least the mandated blend (θ_t) of the total fuel use including the preblended fuel and E100 in year t. [7] We use the blend rate standard by the EPA to reach the quantity mandate of RFS (EPA, 2007).

The vehicle stock dynamics are defined from equation 6.1 to 6.3 with the age characteristics, which allows us to update the age distribution of the vehicle stock at each year t. Equation 6.1 defines the *age1* group of vehicle stock in year *t* is the amount of new purchases of both types of the vehicle. Equation 6.2 shows the other age groups of *a* in year *t* is the amount of vehicle stock from the previous year *t-1* at age *a-1* minus the possible early retirement. Equation 6.3 shows the initial level of the vehicle stock for each age group *a* in year *t1* is determined by the baseline condition $v_a^{0,i}$, which is exogenously assigned while considering the early retirement.

3.1 Analytical implications

By using the Karush Kuhn-Tucker (KKT) theorem, the first-order conditions of key decision variables of equation A1 to A11 are attached in appendix A.1. The KKT theory implies zero

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[7] The highest ethanol blends could be taken by CV is κ=10%, which is also the current blend wall.

marginal profit conditions hold for all stake-holders with the interior solution.

3.1.1 Fuel taxes and subsidies

From the first-order conditions of the preblended fuel (equation A2) and E100 (equation A3) on an energy equivalent basis, we have following results:

$$P_B^{gge} = \lambda_t^{1,i} = \kappa S_t^{e,n}/\xi + (1-\kappa)S_t^{g,n}/\xi + (\theta_t - \kappa)\lambda_t^4/\xi \tag{7}$$

$$P_E^{gge} = \lambda_t^{1,FFV} = S_t^{e,n}/(2/3) - (1-\theta_t)\lambda_t^4/(2/3) \tag{8}$$

First, consumer prices on the left-hand sides $P_B^{gge} = \lambda_t^{1,FFV} = P_E^{gge}$ indicates that the consumer prices of blended fuel and ethanol are equivalent on basis of \$/gge (gasoline gallon equivalent), similar to the results as of Khanna et al (2016). The FFV owners are indifferent between two fuels that could drive on any blend of E10 and E100. On right hand side of equation 7 for preblended fuel, $\kappa S_t^{e,n}/\xi + (1-\kappa)S_t^{g,n}/\xi$ is the marginal production cost, on top of which implicit tax $t^B = (\theta_t - \kappa)\lambda_t^4/\xi$ is from the blend constraint. Conversely, pricing of ethanol besides the marginal production cost in equation 8 shows an implicit subsidy $s^E = (1-\theta_t)\lambda_t^4/(2/3)$ for ethanol consumers. The results of implicit subsidies on ethanol and implicit taxes on low blends of preblended fuel are similar with the analytical results (Cui et al., 2011; Lapan and Moschini, 2012).

Results from the graphical analysis is consistent with the above analytical results. As illustrated in Figure 1 in dashed lines, when the blend mandate was first implemented and lower than the blend wall of 10%, the consumer demand curve of gasoline shift inward proportionally (from D^{G_0} to D^{G_b} in Figure 1g) with a percentage of θ_t replaced by ethanol. Preblended ethanol demand curve shifts outward (from D^{E_0} to D^{E_b} in Figure 1d). When the mandate rates go further beyond the blend wall predicted after 2017, more E100 is needed as demand curve in Figure 1e shifts outward from D^{H_0} to D^{H_q} while more gasoline demand is replaced by ethanol from D^{G_0} to D^{G_q}. The price wedge in Figure 1f, s^E at ethanol supply of TE^*, shows the implicit subsidy on ethanol. The tax on preblended fuel from blending ethanol in (d) and gasoline in (g) is the weighted sum of s^{E_b} and t^G with the blend rate κ.

We can draw more implications from the algebraic forms of t^B and s^E. First, when the RFS blend mandate is more stringent with a higher blend rate θ_t, shadow price (λ_t^4) increases that leads to more intensified of implicit tax/subsidy on fuels. Under conditions of highly stringent blend rate mandate, the consumer prices could differ with $P_B^{gge} > P_E^{gge}$ with the corner solution. The lower ethanol price would attract FFV owners to only purchase E100 while CV owners use E10. Therefore, the vehicle owners would be stimulated to use more FFVS, and to retire the existing CVs.

3.1.2 Implicit taxes/subsidies for newly purchased vehicles

The analytical results quantify the policy mechanism for the vehicle drivers. Table 1 shows the first order conditions (FOCs) breakdown for both the existing vehicle (condition 1) and newly purchased vehicle (condition 2). The condition 1 vehicles are purchased precedingly that are drivable as an option and will be terminated after reaching the maximum life-time (24 years for this study) without any remaining scrappage value. The condition 2 vehicles are newly purchased during the study period T that, if still in use by the end of the year T, could recover its terminal scrappage value based on the age. Derivation can be found in Appendix A.2 and A.3.

To decide whether to keep an existing vehicle at age *a*, or buy a new one in year t, with the interior solution, marginal benefit should at least cover the marginal cost of running this vehicle. As shown in Table 1, the yearly accumulative marginal benefit, O&M cost, fuel cost, and implicit RFS instruments are similar for both conditions. Whereas, the rest onetime payments of initial and terminal status differ in nature of the vehicle stock. Condition 1 vehicle owner has a shadow prices $\lambda_{a}^{5\_3,i}$ as one-time penalty of running the old car from constraint 6.1 in year t1, whereas condition 2 vehicle owner pay for initial cost φ^{i} without any terminal value left.

Inferred from appendix A.3, the vehicle policy instruments are derived from implicit taxes/subsidies via the fuel use behavior. Further policy implication from the algebraic results are expanded in following aspects: (1) RFS stringency; (2) variation across years and ages; (3) intensity of the instrument comparison for FFV versus CV drivers. First, a stringent RFS blend rate mandate (θ_{t}) leads to a higher subsidy on FFVs and heavier tax on CVs. Similar with the conclusion from 3.1.1, a more stringent policy constraint indicates a higher shadow price (λ_{t}^{4}), which leads to higher values of the vehicle instruments as shown in the last column in Table 1. Overall, the older cars of both types are to be replaced by the newer FFVs with a marginal increase in the stringency of the policy.

Second, the annual vehicle policy instruments differ with age and time of purchase due to differences in fuel efficiency and maximum VMT capacity. The intensity of the policy decreases when having a rigid fuel efficiency standard. The higher fuel economy ($\gamma_{a,t}^{i}$) for newer and younger cars requires less fuels. Meanwhile, the aging condition also impairs vehicle function on the mileage capacity (ς_{a}) of a vehicle. But the direction of annual policy instrument change is ambiguous concerning three changing parameters $\gamma_{a,t}^{i}$, ς_{a}, and θ_{t} in the analytical form.

Moreover, we find that the implicit subsidy rates imposed on FFVs are higher than the implicit tax rates on CVs for any age group in year t, as expanded on Appendix A.4. Mainly because of the smaller vehicle stock, the fewer VMT consumptions (multiplication of the fuel economy and fuel consumption) in the denominator leaves FFV with higher subsidy from the revenue neutrality condition. In other words, the intensity of policy instruments depends on the relative VMT consumption power that is mainly driven by the market fleet share.

Though the market pricing mechanism of supporting FFVs is generated by imposing an annual subsidies/taxes on the vehicles, one-time payments or lump-sum subsidy/tax as what we showed in the aggregation form on FFVs and on CVs are suggested to be more effective. As mentioned in Busse et al., (2013) and Miotti et al., (2016), if myopic consumers have a higher discount rate, the future costs or benefits are trivial that makes the annualized policy instrument unattractive. We will continue our discussion about the vehicle instrument using the aggregated one-time payment in the following numeric analysis.

4 Data description for simulation

Most data are from the comprehensive survey of the literature, which includes academic studies, technical reports and government agency reports. The details of data are demonstrated in the three categories as follows.

4.1 Vehicle

The existing national vehicle stock in 2006 is from the EIA (2009) with 4.71 million FFVs and 217.71 million CVs. The initial age distribution of CVs in 2006 follows the percentage distribution from a closer year of National Household Travel Survey (DOT, 2009). The age distribution for FFVs is calculated based on the yearly net increase of FFV stock from 1995 to 2006 (Davis et al., 2015).

A national average price of a new CV sale is set as $28.4 thousand (McLEAN, 2007). Based on the data of manufacturer suggested retail price provided since 2009 (DOE, 2017b), we use market shares of each manufacturer in the U.S. to find the weighted average of the price gap used for FFV vehicle price at $30 thousand. This $1,600 price difference is within range of the recent state policy tax credit from $750 to $3,750 granted for new FFV purchases (AFDC, 2017). Vehicle O&M costs have two parts according to AAA (2016): an annual fixed cost of

$1,070/year, including insurance, license, and plate renewal; and the maintenance cost of $0.0583 /mi including oil and tire changes that are equivalent for both types. The fuel efficiency of CV at 20 miles/gge in 2006 (DOT, 2017), whereas the energy equivalent fuel efficiency of FFV in 2006 is close to 19 mile/gge (DOE, 2017b). The projected annual increase in fuel economy from the EIA (2009) ranges from 0.33% to 2.16% for CV and 0.66% to 1.76% from 2007 to 2040.

4.2 VMT demand

The linear inverse demand curves for the VMT of each vehicle type are calibrated in 2007 by using mileage consumption from both types of vehicles, an estimated cost per mile, and an assumed elasticity of demand for mileage. The mileage consumption is obtained using EIA estimation as benchmark in 2006 (EIA, 2009). The baseline driving cost per mile traveled is from Chen et al., (2014). The VMT demand curve of each type is projected to shift outwards using the annual projections from 2007 to 2040 based on the data of EIA (2009), while the slope of the demand curve remains constant at the 2007 level. The maximum vehicle capacity is calibrated and assumed to drop from 12,500 miles per year to 10,000 miles per year afterward, after it reach the average lifespan of a vehicle.

4.3 Fuel supply

All gasoline is assumed to include a minimum blend of 3.5% ethanol to meet the oxygenate additive requirement. For the RFS scenario, for years before 2010, we set the maximum ethanol content according to the updated final rules by EPA as percentage blend rate and calibrate it to the ethanol level accordingly. And we make a linear projection of the ethanol production for the following years until reaches 35 billion gallons in the target year.

We calibrate the short-run supply elasticity of domestic gasoline using 0.29, which is within the reported range of 0.2-1.61 by many studies (Cui et al., 2011; de Gorter and Just, 2009; Pouliot and Babcock, 2014). The net gasoline supply curve from the rest of the world to the US and its price responsiveness use the same parameters from Oliver and Khanna (2015). Also, the long-term elasticity of the ethanol supply curve of 7.8 is calibrated that within the range of 0.2-13.9 from literature reports (Cui et al., 2011; Luchansky and Monks, 2009; Rask, 1998). The calibrations are based on the average level of benchmark fuel consumption and fuel prices observed from 2006 and 2007 (EIA, 2016; Nebraska Energy Office, 2007).

5 Simulation and discussion

We first validate the simulation model for 2007 assuming existing fuel taxes, RFS, and ethanol tax, and compare the simulated results with the corresponding observed values for fuel use, prices, and vehicle stock in 2007. From Table 2, the deviations of the output from the observed fuel use, fuel price, vehicle stock and VMT are typically less than 10%. This deviation level is similar to the validation tolerance level in other simulation models (Chen et al., 2014; Nuñez and Önal, 2016). This indicates that our stylized model provides a reasonable approximation of the observed market conditions in the fuel and vehicle sectors in the US.

5.1 Scenarios

Following the framework of the analytical model, we first simulate a no-policy baseline scenario (business-as-usual, BAU) and RFS scenarios on track of original 2022 schedule (2007-2022). We updated the blend rate accordingly until 2017 (EPA, 2016) and used the blend rate based on the mandated ethanol quantity of 36 billion gallons to calibrate the blend.

We explore the potential technological development in: (1) competitive FFV purchase price identical to CV; (2) competitive fuel economy of FFV identical to CV (3) the composite improvement of both purchase price and fuel economy. We intend to use the above simulations to explore the mechanism of corresponding policy changes and compare the vehicle and fuel market responses.

We then carry out sensitivity analysis on two more time frames of the RFS by different speeds of blend rate stringency to achieve the quantity target: RFS extended to 2030 (2007-2030) according to projection of the EIA (2009) and as with RFS mandate in Chen et al (2014); and RFS extended to 2040 (2007-2040) from estimation on EIA (2014) that falls short of the target even in 2040. The varying speeds of achieving the RFS quantity goal for those scenarios are assumed constant after 2017 until the end of the simulation. We unify the ending year to 2040 to set a comparable reference point to study the long-run effect of the policy given different RFS time frameworks. Therefore, we maintain the ethanol production level at 36 billion gallons for scenario 2022 and 2030 after reaching the target until 2040.The model is not intended to forecast the future but is best suited for analysis that focuses on relationships, interactions, and trends rather than on single-point estimation.

5.2 BAU scenario

The level of main results of fuel and vehicle sectors at the year 2040 and their annual rate of change are given in the first column in Table 5.In the absence of any government intervention in biofuel market, the BAU scenario is still subject to a 3.5% minimum blending rate of ethanol to meet the oxygenate additive requirement with fuel choices of E100 and preblended fuel with blend rate less than 10%. We find the fuel demand of E100 are zero while preblended fuel use at a rate of 3.5% is dominantly consumed for both vehicles, even though the consumer prices of both fuels are equivalent and decreasing at an annual rate of 0.9% on average. The FFV stock reduces to 0 at 2030 while constant CV stock remain at 224 million. The BAU scenario provides a baseline for comparison of the impact of various time paths of RFS in the following parts.

5.3 RFS scenario

Retail E100 is priced lower than its energy content as with E10 to the extent to attract FFV users consume higher blends and stimulate FFV purchase. In line with the results from the analytical model in section 3.1.1, a feebate system on fuel choices is observed with increasing implicit tax on preblended fuel and implicit subsidy on E100. The results of the fuel prices and feebate based on RFS scenario with 2022 schedule are showed in Figure 2. The declining supply of preblended fuel reduces the producer price in Figure 2a, but the increasing implicit taxes on E10 after 2017 raise the prices for consumer ranging from $2.65/gge to $3.15/gge. In contrary, an increasing demand for ethanol elevates the producer prices and becomes constant when ethanol target reaches the 36-billion-gallon goal after 2022. With this increasing stringent policy, implicit subsidies on E100 increase, which cheapens the consumer price below the E10 consumer prices at $0.71/gge to $2.72/gge. These extra explicit subsidies going below the E10 consumer prices would serve as compensation for the higher purchase cost and lower fuel economy of FFV to incentivize the FFV purchase. An additional 14% in excess to fuel compensation annually is granted to new FFV purchase after 2017. Therefore, the total subsidy on E100 not only supports the FFV users to equalize fuel prices, but also offset the differences in vehicle cost and in fuel economy. Consequently, for those years E100 prices cheaper than E10, FFV owners prefer E100 fuel that rests a corner solution of zero E10 consumption and predominant E100 use. The ethanol consumption under RFS 2022 schedule expands, of which 68% is used by FFV as E100 in excess to the preblended ethanol in the form of E10. The subsidy flows to the consumers resulting in lower ethanol prices beyond the blend wall from corn ethanol is similar with the finding from Stock (2015).

Figure 3 displays the lifelong accumulated cost and benefit of a CV or FFV purchased in year t, corresponding to analytical results from Table 1. The total lifetime costs (blue lines) of FFV over time t are \$73 to \$852 more expensive than CV, however the total benefit from mileage driven and the terminal value recovered by the end of study period of 2040 balance these differences and break the costs even. As condition 2 vehicles described in Table 1, a similar vehicle cross-subsidization with tax on CV and subsidy on FFV are transferred from fuel cross-subsidization in form of lifetime fuel use. The average total implicit subsidy of \$18,672 is imposed on FFV (the sum of 2 green bars that reduce the total fuel cost in Figure 3b) that cover up to 27% of the lifetime total cost. Of the total subsidy from its fuel use, \$2,453 on average (dark green bar in Figure 3b) is served as the FFV purchase compensation that is accumulated over its lifetime based on the explicit vehicle subsidy from fuel use. This FFV compensation not only offset the drawbacks of \$1,600 higher vehicle price of FFV, but also lower fuel economy on the energy equivalent basis. By comparison, CV buyers bear on average an implicit tax of \$2,776 (red bars in Figure 3a) that takes 4% of their lifetime total cost and raises the fuel use cost. The rest of mileage benefit and O&M cost are identical for both vehicles. With these cross-subsidization incentives, the FFVs expand its market share to 18% of the total fleet with 40.05 million units and contribute 17.3% of total VMT driven by 2040.

5.4 Competitive FFV specification analysis

The competitiveness of FFV is reflected by having lower purchase price or higher fuel economy relative to CV. We study the consumer’s choice under perfect information of those differences in FFV specification and examine sensitivity of the market outcomes and policy implications. FFV specification improvement in sales price is more effective than fuel economy, and its greater competitiveness results in less intensity of market instrument.

Table 3 lists the outcomes under scenarios of different FFV specifications in purchase prices and fuel economy under RFS 2022 setting. Column 1 shows the scenario under original FFV setup (with $1,600 higher initial cost and lower fuel economy relative to CV, denoted as Spec 1), which is the same with RFS 2022 scenario with the original time-path settings. By leveling out the FFV sales price difference, the scenario of identical purchase price with fuel economy remains different is listed in column 2 (denoted as Spec2). We also tested the identical fuel economy scenario with vehicle prices remain different in column 3 (denoted as Spec3). The last scenario with both fully identical specification is listed in column 4 (denoted as Spec4).

The results showed that the cross-subsidization are more moderate for all improved scenarios and the fuel economy improvement not only cut down the fuel consumption but also reduce the intensity of the subsidy/tax on fuels. The scenarios Spec 2 and 3, the single specification improvement, halve the explicit vehicle subsidy on ethanol from $0.35/gge of Spec 1 to around $0.17/gge, while the composite improvement scenario of Spec 4 zeros out this part of the subsidy with identical specifications. With less subsidy on ethanol, Spec 3 and 4 line up the fuel prices of ethanol with preblended fuel. The increases in the ethanol consumer price are caused by both rising marginal cost of ethanol production due to higher demand, and the more moderate tax/subsidy intensity. Nevertheless, an elastic VMT demand curve keeps the fuel consumption at the same level between Spec 1 and 2, but a lower level with higher fuel economy in Spec3 and 4, even the prices greatly across scenarios.

Similarly, both vehicle purchases also experience a declining feebate incentives. The FFV purchase compensation is reduced to levels less than $1,300 in both Spec2 and 3 scenarios, and down to zero in the Spec 4 scenario with completely identical specification. Fuel use compensation reduce by more than $1,200 per vehicle when having higher fuel economy in Spec3 and Spec4 compared to the counterparts without identical fuel economy in Spec 1 and 2.

The taxes on CV decreases for all three scenarios with specification improvement. Neither does the single improvement scenario of Spec2 or Spec 3 stimulate large volume of FFV purchase or make significant fleet structure change. But with fully competitive specification, FFV sales of Spec 4 keeps at the same level with CV that also split the total VMT consumptions.

The welfare analysis in Table 4 shows that the initial purchase cost improvement is more efficient with less welfare loss. Consumer surplus from VMT demand increase for all improved specifications when more FFVs penetrate the market with less loss. The total vehicle purchase cost reduced to 3,989 billion with lower purchase costs in scenarios of Spec 2 and Spec 4, while the Spec3 scenario increases the vehicle purchase cost with greater FFV penetration while FFV price remains more expensive. The O&M cost shows that total VMT driven are constant across scenarios. Both ethanol and gasoline producer surplus shrink when FFV improves fuel economy equivalent with CV. The lower level of the total fuel supply decreases the gain for ethanol while increase the welfare loss for gasoline producers that strike the fuel industry. Lower terminal values are recovered when vehicle prices are lower. In general, the initial cost improvement would benefit the VMT consumer with cheaper FFV and also more VMT consumer surplus. But the fuel economy improvement would strike the fuel production industry with less demand.

5.5 Policy time path sensitivity analysis

Lower speed of RFS implementation would benefit more from lower burden of feebate instrument, higher VMT driving capacity, and lower welfare cost. Different time paths of the RFS under different blend rate schedules from 2007 to 2040 are displayed in Figure 4. Similar with Smith's (2016) analysis that a change in the expected future stringency of the mandate affects RIN prices and compliance costs, the corresponding calibrated blend rate, simulated fuel use, vehicle sectors, and social welfare from demand side are also affected with this dynamic forward-looking model.

Blend Stringency: We noticed that in Figure 4, blend rate of 2022 and 2030 pathways overlap after reaching the quantity mandate and increase along until joint with 2040 scenario at round 33% in 2040. The blend rates increase over time because of decreasing total fuel use due to increased fuel economy. Across the three scenarios, the lower stringency of the longer mandate scenario has lower taxes on preblended fuel (decrease from $0.41/gge for 2022 scenario to $0.35/gge for 2030 scenario and $0.27/gge for 2040 scenario in Table 5), and lower levels of implicit fuel price subsidies on ethanol on average (decrease from $2.35/gge for 2022 scenario to $2.24/gge for 2030 scenario and $2.13/gge for 2040 scenario) while the explicit vehicle subsidy remain relatively stable at $0.33/gge.

Fuel use: RFS scenarios reduce E10 consumption from 89.23 billion gge from BAU to around 73 billion gge for all RFS scenarios. Across the three RFS scenarios, the total fuel use does not vary much in E10 (both blended gasoline and ethanol) and E100 in both quantity and prices. The consumer prices of E10 are raised around $3.16/gge after taxes within three RFS scenarios, while ethanol is much cheaper than E10 in 2040 dragged down by the portion of explicit vehicle subsidy. Compared to BAU scenario, RFS scenarios raises the consumer prices of E10 that makes E100 more attractive for FFV drivers. But overall the fuel market is robust to the different stringency of mandate.

Vehicle purchase: Similar with the decreasing cross-subsidization on the fuel sectors, the implicit taxes on each unit of CVs downscaled from $2.8k in 2022 scenario to $2.4k in 2030 scenario and $1.8k in 2040 scenario, along with decreasing subsidies on FFVs from $18.6k in 2022 scenario down to $17.8k in 2030 scenario and $16.9k in 2040 scenario. If decompose this subsidy, the FFV purchase compensations slightly decrease for longer time paths but generally at level of $2.4k, while the majority of subsidy are used for the fuel price compensation. Notice the aggregated instrument vary by time of purchase and usually peak around year 12 and 13 (as showed in Figure 3). It is because the later purchase may not drive to its maximum age span until 2040 while having more stringent mandate policy. The substantial subsidy on FFV in total, which is 7 to 12 times higher than the tax on CV, is due to small FFV stock share when satisfying the revenue neutral condition.

Driving demand: We also observe a slower increase rate of the FFV stock with longer duration scenarios when the speed of CV replacement remains constant. The average FFV penetration rate slow down from 8.8% of RFS2022 to 7.0% of RFS2030, and down to 6.9% of RFS2040 annually. The levels of total VMT are identical for all scenarios including BAU, whereas more weight is put on FFV for the longer duration scenario when later FFV purchases are still in good condition by 2040 and have higher mileage capacity as assumed before age 15.

Social welfare: The welfare analysis of the above scenarios from 2007 to 2040 is also shown in Table 4. The overall discounted welfare loss because of the RFS compliance of longer time paths declines with $338 billion (0.1% loss), $275 billion (0.08% loss), and $210 billion (0.06% loss), the majority of which are caused by VMT consumer surplus loss. The inelastic mileage demand curve attributes to the substantial decrease in VMT consumer surplus loss, and also relatively stable O&M cost proportional to VMT consumption. We also observe the declining vehicle purchase costs when less FFV purchases are incentivized throughout the study period.

In comparison to only $9 billion contributions by ethanol in total producer surplus under the BAU, the ethanol producers gain by taking more than 20% of the total producer surplus in all RFS scenarios. Overall, the fuel producer welfare gains become lower with longer time paths of RFS from $295, $239, to $189 billion. Meanwhile, gasoline producer losses also diminish when lower intensified implicit taxes from RFS on preblended fuel lower the demand for gasoline production. The results are consistent in the directions of welfare gain for ethanol producers and loss for gasoline producers due to the compliance of RFS blend mandate with the study of Khanna et al (2016).

6 Conclusion

This paper develops a stylized partial equilibrium welfare economic model to examine the consumer incentives to buy higher ethanol blends and switch to FFV under implicit RFS policy instruments implemented. The model is meant to provide the underlying mechanism of RFS mandate for consumers. We also simulate numerically the cases for policy design purpose under current tendency with 1) the longer time paths of achieving RFS mandate and 2) the scenarios with greater competitiveness of FFV in terms of purchase price or fuel economy as with CV. The present study contributes to the related literature with policy analysis targeted at consumers to induce a shift towards renewable fuels and FFVs to comply with RFS, and extends the modelling by considering the vehicle dynamics and structural changes.

The results showed a higher blend rate mandate going beyond the blend wall to supplement RFS requires a combination of cross-subsidization on both fuel and vehicle markets: subsidy on E100 and tax on preblended fuel along with subsidy on FFV and tax on CV. The subsidy on FFVs transferred from fuel use subsidy not only drives down the consumer price of E100 lower than E10, but also offset the drawbacks costs of FFV to incentivize the vehicle owners to switch to FFV and buy higher ethanol blend.

We also find that longer policy duration reduces the cross-subsidization on both fuels and vehicles while the fuel markets are robust in both fuel consumption and consumer prices. The slower time paths also introduce later FFV purchases that contribute more to the VMT capacity, while also allow more time for FFV to have technology development. Welfare analysis showed longer time paths reduce both welfare loss to the gasoline producers and welfare gain of the ethanol producers.

By improving the FFV sales price, vehicle drivers benefit more from lower vehicle cost, while fuel producers bear more loss from improved fuel economy. The higher competitiveness of FFV compared to CV downgrades the feebate intensities on both fuel and vehicle sales. The vehicle purchase subsidies plunge to zero with fully identical scenario.

In general, these results from both analytical and simulative work infer a series of demand-side incentives with cross-subsidization system both in fuels consumption (tax on preblended fuel and subsidy on E100) and vehicles purchase (tax on CV and subsidy on FFV). The intensity of these feebate system depends not only on the stringency of the policy, but also the competitiveness of the vehicle specification.

Note that the conclusion held only when demand-side motivations are explicitly pronounced with well-informed subsidy/tax for fuel consumers on energy equivalent basis and the upfront payment of subsidy/tax on vehicles built-in through fuel use. This enable the transparency of pricing of alternative fuels that encourage price competition for vehicle owners that solves for the incomplete pass-through of RIN subsidies to fuel consumers.

The longer timelines of the RFS mandates addressed in this study proposes an efficient and flexible regime to follow that matches well with the current modified RFS regime. More details as to the form of the mandate either in quantity or blend mandate, the feedstock of the ethanol, rulemaking in form of annual or multi-year to reduce the uncertainty could be further studied by expanding the framework of this model.

This study is a general framework that could be further developed by considering the limitation in the availability of ethanol or FFV, and including other alternative vehicles like electric vehicle or natural gas vehicle to broaden the vehicle market equilibrium.

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Figures and Tables

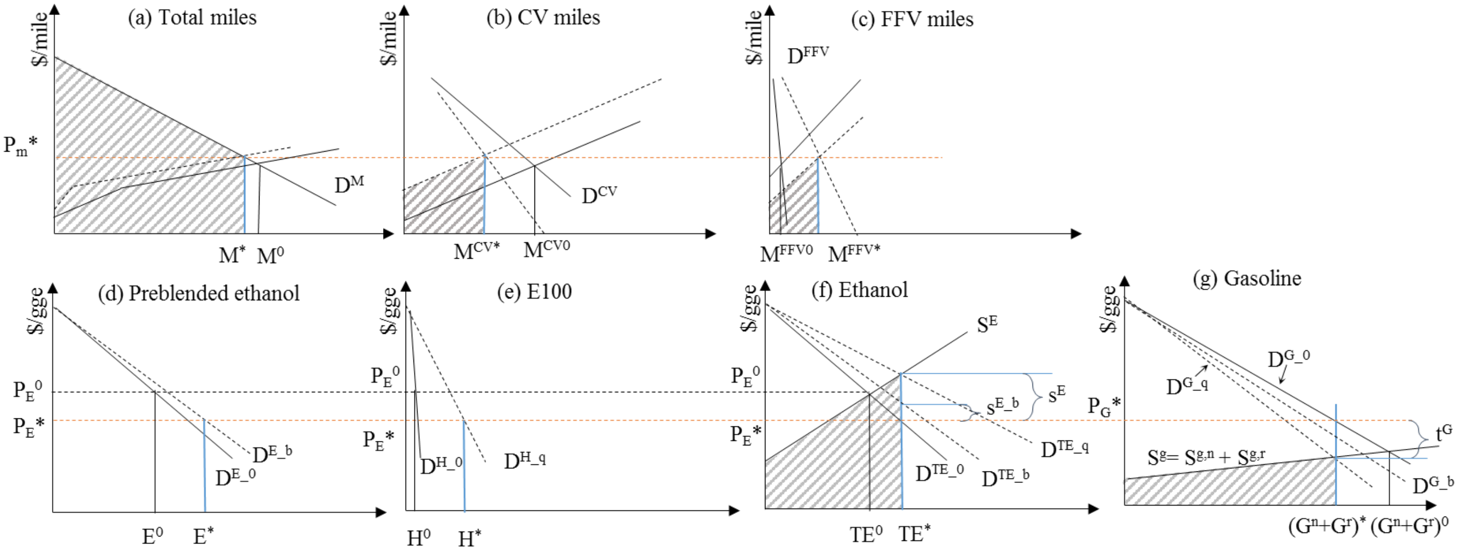


Figure 1 Effect of status quo policies on the fuel and VMT market

Note: The market equilibrium of business-as-usual scenario are denoted with 0 in the superscript for both variables and curves; The RFS policy equilibrium uses the star in the superscript. The superscript b in the demand curve change refers to the ethanol policy shock within the blend wall. The superscript q is the ethanol policy shock beyond the blend wall.

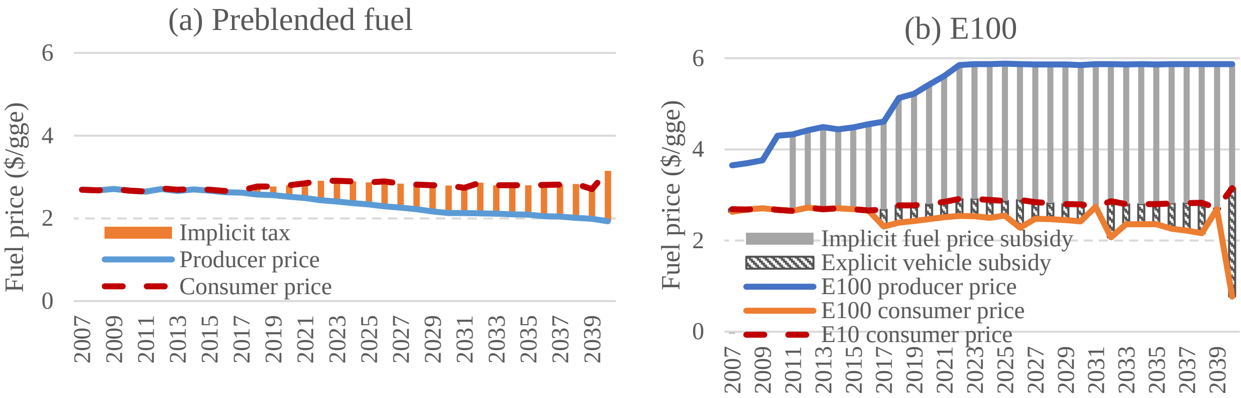
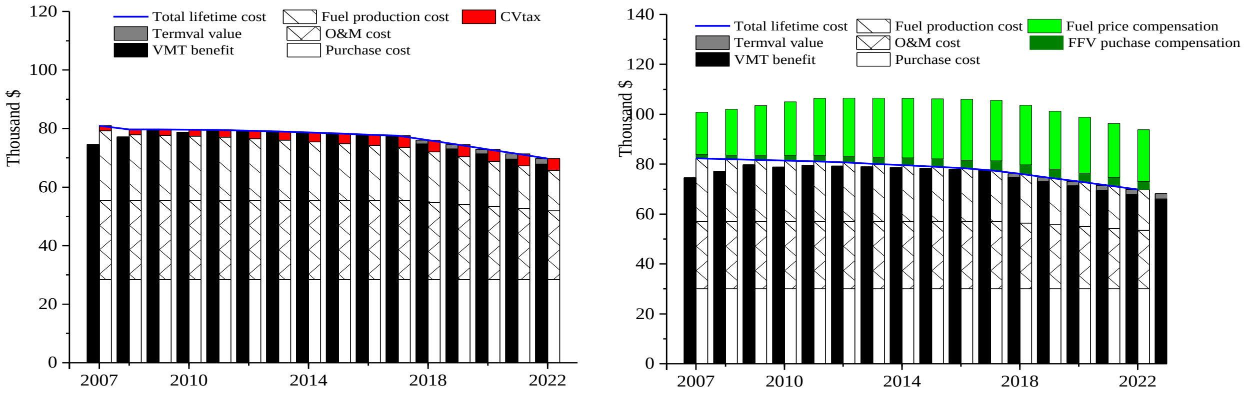


Figure 2 Fuel prices and market feebate pricing

Note: The implicit fuel subsidy of E100 level out price of E100 to the same level as preblended fuel. And explicit vehicle subsidy lower the consumer price of E100 lower than E10 to incentivize FFV owner to use exclusively E100, and thus to stimulate FFV purchase.



a) Conventional Vehicle

b) Flexible fuel vehicle

Figure 3 The benefit-cost pairwise analysis for new vehicle purchase over lifetime in year t

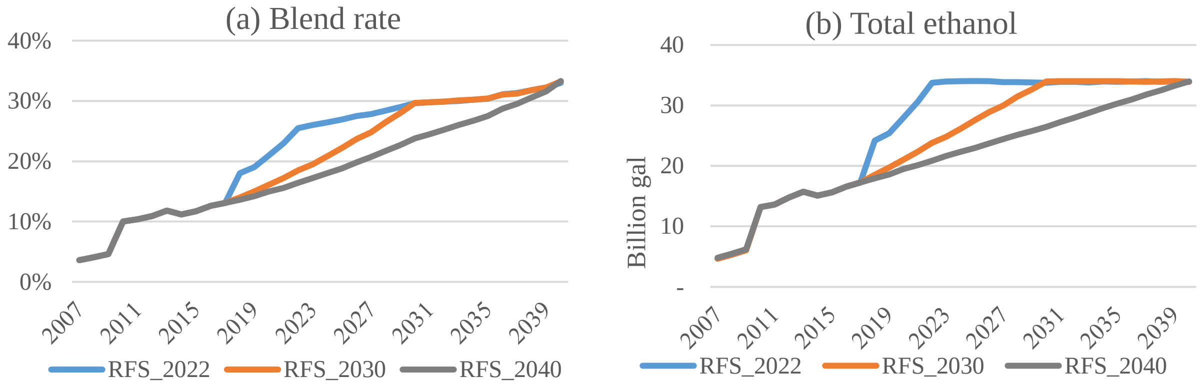


Figure 4 The blending schedule and its corresponding ethanol production

Note: RFS_2022 is the original RFS policy scenario that reaches the 35 billion gallon of ethanol target in 2022; RFS_2030 scenario reaches the same ethanol target in 2030; RFS_2040 scenario delayed the target year to 2040

Table 1 Breakdown of FOC for lifetime vehicles use

	Marginal benefit		Marginal cost			
	Benefit from VMT driven	Recovered terminal value	Capital cost	O & M cost	Fuel cost[8]	Vehicle incentive[9]
Condition1: from t0 to age 24, retire before t=T						
CV	$\sum_{k=0}^{\mathrm{a}24-a+1} \rho^k \varsigma_{\mathrm{a}+k} D_{t1+k}^m$	--	$\lambda_a^{5\_3,CV}$	$\sum_{k=0}^{\mathrm{a}24-a+1} \rho^k (\varsigma_{\mathrm{a}+k} \eta^{CV} + \varepsilon_a)$	$\sum_{k=0}^{\mathrm{a}24-a+1} \rho^k \varsigma_{\mathrm{a}+k} S_{a+k,t1+k}^{CV}$	$\sum_{k=0}^{\mathrm{a}24-a+1} \rho^k \varsigma_{\mathrm{a}+k} t_{a+k,t1+k}^{CV}$
FFV		--	$\lambda_a^{5\_3,FFV}$	$\sum_{k=0}^{\mathrm{a}24-a+1} \rho^k (\varsigma_{\mathrm{a}+k} \eta^{FFV} + \varepsilon_a)$	$\sum_{k=0}^{\mathrm{a}24-a+1} \rho^k \varsigma_{a+k} S_{a+k,t1+k}^{FFV}$	$-\sum_{k=0}^{\mathrm{a}24-a+1} \rho^k \varsigma_{\mathrm{a}+k} \mathrm{s}_{a+k,t1+k}^{FFV}$
Condition2: from any t to T						
CV	$\sum_{k=0}^{T-t+1} \rho^k \varsigma_{\mathrm{a}+k} D_{t+k}^m$	$\beta \varphi^{CV} \pi_{\mathrm{a}+T\text{-}\mathrm{t}} \rho^{T-t+1}$	φ^{CV}	$\sum_{k=0}^{T-t+1} \rho^k (\varsigma_{\mathrm{a}+k} \eta^{CV} + \varepsilon_a)$	$\sum_{k=0}^{T-t+1} \rho^k \varsigma_{\mathrm{a}+k} S_{a+k,t+k}^{CV}$	$\sum_{k=0}^{T-t+1} \rho^k \varsigma_{\mathrm{a}+k} t_{a+k,t+k}^{CV}$
FFV		$\beta \varphi^{FFV} \pi_{\mathrm{a}+T\text{-}\mathrm{t}} \rho^{T-t+1}$	φ^{FFV}	$\sum_{k=0}^{T-t+1} \rho^k (\varsigma_{\mathrm{a}+k} \eta^{FFV} + \varepsilon_a)$	$\sum_{k=0}^{T-t+1} \rho^k \varsigma_{\mathrm{a}+k} S_{a+k,t+k}^{FFV}$	$-\sum_{k=0}^{T-t+1} \rho^k \varsigma_{\mathrm{a}+k} \mathrm{s}_{a+k,t+k}^{FFV}$

Note:Condition 1 vehicle are existing vehicle still in use and will terminate before the end of study period; Condition 2 vehicle are newly purchased vehicle that will keep in use by the end. The lifetime benefit and cost of driving one vehicle for a vehicle owner should be balanced with interior solution of having at least one. And the VMT benefit, O&M cost, fuel cost, and vehicle incentives are yearly accumulative throughout its lifetime use.

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[8] For simplicity, we define fuel production cost for CV and FFV as S ($/mi) and let

$$S_{a,t}^{CV} = \frac{\kappa_{\mathrm{t}} S_{\mathrm{t}}^{\mathrm{e,n}} + (1-\kappa_t) S_{\mathrm{t}}^{g,n}}{\xi \gamma_{\mathrm{a,t}}^{CV}} \text{ and } S_{a,t}^{FFV} = \frac{S_{\mathrm{t}}^{e,n}(\kappa_t B_{\mathrm{t}}^{FFV} + H_t) + S_{\mathrm{t}}^{g,n}(1-\kappa_t) B_{\mathrm{t}}^{FFV}}{\gamma_{\mathrm{a,t}}^{FFV}(B_{\mathrm{t}}^{FFV} \xi + H_t \frac{2}{3})}$$

[9] Similarly, we let implicit tax on the CV and implicit subsidy on the FFV mile consumers ($/mi), as $t_{a,t}^{CV} = \frac{(\theta_t - \kappa_t)\lambda_t^4}{\xi \gamma_{\mathrm{a,t}}^{CV}}$ and $s_{a,t}^{FFV} = \frac{\lambda_t^4 (H_t(1-\theta_t) - B_{\mathrm{t}}^{FFV}(\theta_t - \kappa_t))}{\gamma_{\mathrm{a,t}}^{FFV}(B_{\mathrm{t}}^{FFV} \xi + H_t \frac{2}{3})}$. It could be further separated according to the definition of the fuel price compensation or vehicle purchase compensation

Table 2 Model calibration for 2007

		Observed data	Simulated output	Difference (%)
Fuel use (Billion gallon)	Gasoline	130	124.67	-4%
	Ethanol	4.74	4.79	1%
Producer prices ($/gal)	Gasoline	2.74	2.66	-3%
	Ethanol	2.31	2.44	6%
Vehicle stock (million)	CV	220.36	215.88	-2%
	FFV	5.5	4.74	6%
VMT (B mi)	CVS	2579.6	2495.0	-3%
	FFV	64.9	59.25	-9%

Table 3 The effects of FFV specifications on transportation sector

	Spec1	Spec2	Spec3	Spec4
Average fuel tax in $/gge				
Preblended fuel	0.41	0.39	0.39	0.36
E100[b] Implicit fuel price subsidy	-2.35	-2.52	-2.37	-2.40
Explicit vehicle subsidy	-0.35	-0.17	-0.18	0
Fuel consumption in billion gge[a]				
Preblended fuel	73.10	73.09	71.85	71.84
Blended gasoline	68.06	68.05	66.89	66.89
Blended ethanol	5.04	5.04	4.95	4.95
E100	17.56	17.56	17.26	17.26
Total fuel use	90.66	90.65	89.11	89.10
Fuel consumer prices in $/gge[a] (average annual change)				
Preblended fuel	3.15	2.79	3.06	2.66
	(0.53%)	(0.11%)	(0.43%)	(-0.03%)
E100	0.77	2.3	2.96	2.66
	(-1.79%)	(-0.29%)	(-1.81%)	(-0.03%)
Gasoline	3.33	2.82	3.22	2.66
	(0.73%)	(0.15%)	(0.60%)	(-0.03%)
Average implicit vehicle tax in $/unit (average % of lifetime total cost)				
CV	2,776	2,597	2,617	2,424
	(4.3%)	(4.0%)	(4.1%)	(4.0%)
FFV[b] Fuel use compensation	-16,219	-16,415	-14,924	-15,117
	(54%)	(20%)	(18%)	(18%)
Vehicle purchase compensation	-2.453	-1,251	-1,186	0
	(8.2%)	(1.9%)	(2.0%)	(0%)
Vehicle stock structure in million[a] (annual penetration rate)				
CV	183.45	183.4	180.3	110.62
	(-0.48%)	(-0.48%)	(-0.53%)	(-1.97%)
FFV	40.05	40.03	43.1	112.78
	(8.82%)	(8.82%)	(9.16%)	(11.03%)
VMT in billion mile[a]				
CV	2,063	2,062	2,030	1,236
FFV	434	433	466	1,259
Total	2,497	2,496	2,496	2,495

Note: Spec1 denotes the scenario under original FFV specification (with $1,600 higher initial cost and lower fuel economy relative to CV; Spec2 is the scenario of identical purchase price with fuel economy remains different; Spec3 is the identical fuel economy scenario with vehicle prices remain different; Spec4 described the fully identical specification of FFV in both initial sales price and fuel economy.

[a] *The value in 2040*

[b] *Negative values denote the subsidy*

Table 4 The welfare implication of different FFV specification from 2007 to 2040

	Spec1	Spec2	Spec3	Spec4
VMT consumer surplus	340,021	340,055	340,081	340,118
	(-483)	(-449)	(-432)	(-395)
Vehicle purchase cost	4,023	3,989	4,026	3,989
	(29)	(-5)	(31)	(-5)
Operations and management cost	7,314	7,314	7,315	7,315
	(-5)	(-5)	(-5)	(-4)
Ethanol producer surplus	303	303	297	297
	(295)	(295)	(288)	(288)
Gasoline producer surplus	730	730	724	724
	(-130)	(-130)	(-135)	(-135)
Recovered terminal value	341	336	340	336
	(5)	(0)	(4)	(0)
Total social surplus	330,057	330,121	330,101	330,170
	(-338)	(-274)	(-294)	(-225)

Note: Spec1 denotes the scenario under original FFV specification (with $1,600 higher initial cost and lower fuel economy relative to CV; Spec2 is the scenario of identical purchase price with fuel economy remains different; Spec3 is the identical fuel economy scenario with vehicle prices remain different; Spec4 described the fully identical specification of FFV in both initial sales price and fuel economy. And numbers in the parentheses are welfare changes compared to counterpart BAU scenarios

Table 5 The effects of time path of RFS on fuel and vehicle use, and policy instruments

		BAU	Original RFS policy targeted in 2022	RFS policy targeted in 2030	RFS policy targeted in 2040
Blend rate in %[a]		3.5	33	33.2	33.3
Average fuel tax in $/gge					
Preblended fuel		0	0.41	0.35	0.27
E100[b]	Implicit fuel price subsidy	--	-2.35	-2.24	-2.13
	Explicit vehicle subsidy	--	-0.35	-0.34	-0.33
Fuel consumption in billion gge[a]					
Preblended fuel		89.23	73.10	73.13	73.07
	Blended gasoline	87.12	68.06	68.09	68.03
	Blended ethanol	2.11	5.04	5.04	5.04
E100		0	17.56	17.57	17.60
Total fuel use		89.23	90.66	90.70	90.67
Fuel consumer prices in $/gge[a] (average annual change)					
Preblended fuel		2.02 (-0.9%)	3.15 (0.53%)	3.16 (0.53%)	3.16 (0.54%)
E100		2.02 (-0.9%)	0.77 (-1.79%)	0.75 (-1.94%)	0.76 (-1.92%)
Gasoline		2.02 (-0.9%)	3.33 (0.73%)	3.34 (0.73%)	3.34 (0.74%)
Average implicit vehicle tax in $/unit (average % of lifetime total cost)					
CV		0 (0%)	2,776 (4.3%)	2,382 (3.7%)	1,805 (2.9%)
FFV[b]	Vehicle purchase compensation	--	-2,453 (8.2%)	-2,420 (8.1%)	-2,373 (7.9%)
	Fuel price compensation	--	-16,219 (54%)	-15,424 (51%)	-14,555 (48 %)
Vehicle stock structure in million[a] (annual penetration rate)					
CV		226.8 (0.1%)	183.45 (-0.48%)	183.26 (-0.48%)	183.12 (-0.49%)
FFV		0 (-7.2%)	40.05 (8.82%)	40.26 (7.01%)	40.40 (6.86%)
VMT in billion mile[a]					
CV		2,499	2,063	2,046	2,026
FFV		0	434	451	471
Total		2, 499	2,497	2,497	2,497

[a] *The value in 2040*

[b] *Negative values denote the subsidy*

Table 6 The welfare implication of different time paths of RFS from 2007 to 2040

	BAU	Original RFS policy targeted in 2022	RFS policy targeted in 2030	RFS policy targeted in 2040
VMT consumer surplus	340,505	340,021	340,124	340,227
		(-483)	(-380)	(-278)
Vehicle purchase cost	3,994	4,023	4,022	4,020
		(29)	(27)	(25)
Operations and management cost	7,319	7,314	7,315	7,316
		(-5)	(-4)	(-3)
Ethanol producer surplus	9	303	248	198
		(295)	(239)	(189)
Gasoline producer surplus	860	730	744	755
		(-130)	(-116)	(-105)
Recovered terminal value	336	341	341	342
		(5)	(5)	(6)
Total social surplus	330,395	330,057	330,120	330,186
		(-338)	(-275)	(-210)

**Numbers in the parentheses are welfare changes compared to counterpart BAU scenarios*

Appendix A Derivation

A.1 Karush Kuhn-Tucker conditions and economic implication

By taking the derivative with respect to the key variables, we have following results:

$$[M_{i,\mathrm{a},t}]\quad D_m = \eta + \lambda_t^{1,i} / \gamma_{i,\mathrm{a}} + \lambda_{\mathrm{a},t}^{2,i} \quad \forall \mathrm{i}, a, t \tag{A1}$$

$$[B_{i,t}]\quad \xi_t \times \lambda_t^{1,i} = \kappa \lambda_t^{3E} + (1-\kappa)\lambda_t^{3G} + (\theta_t - \kappa)\lambda_t^{4} \quad \forall \mathrm{i,t} \tag{A2}$$

$$[H_t]\quad 2/3 \times \lambda_t^{1,FFV} = \lambda_t^{3E} - (1-\theta_t)\lambda_t^{4} \quad \forall \mathrm{t} \tag{A3}$$

$$[G_t^{n,d}]\quad \lambda_t^{3G} = S_{\mathrm{t}}^{\mathrm{g,n}} \quad \forall t \tag{A4}$$

$$[E_t^{n,d}]\quad \lambda_t^{3E} = S_t^{\mathrm{e,n}} \quad \forall t \tag{A5}$$

$$[N_{\mathrm{i,t}}]\quad \lambda_t^{5\_1,i} = \varphi^i \quad \forall i,t \tag{A6}$$

$$[V_{\mathrm{i,a1,t}}]\quad \varsigma_{a1}\lambda_{a1,t}^{2,i} + \rho\lambda_{a2,t+1}^{5\_2,i} = \lambda_t^{5\_1,i} + \varepsilon = \varphi^i + \varepsilon_{a1} \quad \forall i, t > t2 \tag{A7}$$

$$[V_{\mathrm{i,a,t1}}]\quad \varsigma_a \lambda_{a,t1}^{2,i} + \rho\lambda_{a+1,t+1}^{5\_2,i} = \lambda_a^{5\_3,i} + \varepsilon_a \quad \forall i, \mathrm{a} > \mathrm{a2} \tag{A8}$$

$$[V_{\mathrm{i,a,t}}]\quad \lambda_{a,t}^{5\_2,i} - \lambda_{a,t+1}^{5\_2,i}\rho = \varsigma_a \lambda_{a,t}^{2,i}\rho + \varepsilon_a \quad \forall i,\ \mathrm{t2} \le t < T, a2 \le a < a24 \tag{A9}$$

$$[V_{\mathrm{i,a,T}}]\quad \lambda_{a,T}^{5\_2,i}\rho^{\mathrm{T-1}} = \varsigma_a \lambda_{a,T}^{2,i}\rho^{\mathrm{T}} + \beta\varphi^i \pi_a \rho^{\mathrm{T}} + \varepsilon_a \rho^{\mathrm{T}} \quad \forall i, a \ge a2 \text{ and t=T} \tag{A10}$$

$$[V_{\mathrm{i,a24,t}}]\quad \lambda_{a24,t}^{5\_2,i} = \varsigma_a \lambda_{a24,t}^{2,i}\rho + \varepsilon_{a24} \quad \forall i, t < T \tag{A11}$$

A.2 Mileage implications

From equation A1 for both type of the vehicle. Using the result from equation 7 for CV, we have: $D_t^m = \eta + \lambda_{a,t}^{2,CV} + S_{a.t}^{CV} + t_{a,t}^{CV}$ for CV (A12).From equation 7 and equation 8, the consumer price of mileage consumption for FFV is $D_t^m = \eta + \lambda_{a,t}^{2,FFV} + S_{a.t}^{FFV} - s_{a,t}^{FFV}$ (A13).

A.3 Vehicle stock implications

Based on the FOCs from equation A9, the general form of $\lambda_{i,\mathrm{a},t}^{5\_2}$ in time sequence can be written as $\lambda_{\mathrm{a},t}^{5\_2,i} = \lambda_{a+T\text{-t},T}^{5\_2,i}\rho^{T-t} + \sum_{k=1}^{T-t}\rho^k(\varsigma_{a+k\text{-}1}\lambda_{a+k\text{-}1,t+k-1}^{2,i} - \varepsilon_{a+k\text{-}1})$. Substitute $\lambda_{a+T\text{-t},T}^{5\_2,i}$ from equation A10 and plug in the $\lambda_{age,t}^{2,i}$ from equation A12 and A13, it can be rewritten:

$$CV: \lambda_{a,t}^{5\_2,CV} = \sum_{k=0}^{T-t}\rho^k \varsigma_{a+k} D_{t+k}^m + \beta\varphi^{CV}\pi_{a+T\text{-}t}\rho^{T-t+1} - \sum_{k=0}^{T-t}\rho^k[\varsigma_{a+k}(\eta^{CV} + S_{a,t}^{CV} + t_{a,t}^{CV}) - \varepsilon_a]$$

$$FFV: \lambda_{a,t}^{5\_2,FFV} = \sum_{k=0}^{T-t}\rho^k \varsigma_{a+k} D_{t+k}^m + \beta\varphi^{FFV}\pi_{a+T\text{-t}}\rho^{T-t+1} - \sum_{k=0}^{T-t}\rho^k[\varsigma_{a+k}(\eta^{FFV} + S_{a,t}^{FFV} - s_{a,t}^{FFV}) - \varepsilon_a]$$

$\lambda_{a,t}^{5\_2,i}$ can be rewritten with $\rho^{t-1}\lambda_{a,t}^{5\_2,i} = \rho^{t-1}\lambda_a^{5\_3,i} - \sum_{k=1}^{t}\rho^{k-1}\varsigma_a \lambda_{a-t+k,k}^{2,i}$ for condition 1 and also

$\rho^{t-1}\lambda_{a,t}^{5\_2,i} = \rho^{t-1}\eta - \sum_{k=1}^{t}\rho^{k-1}\varsigma_a\lambda_{a-t+k,k}^{2,i}$ for condition 2. Finally, we have the lifelong FOC for both types of the vehicle of two conditions in section 3.1.2.

A.4 Policy implication on vehicle derivation

Based on the constraint equation 5 and reorganized it into $H_t(1-\theta_t) = \sum_i B_t^i(\theta_t - k)$, the numerator on FFV subsidy $H_t(1-\theta_t) - B_t^{FFV}(\theta_t - k) = B_t^{CV}(\theta_t - k)$. Therefore, we have:

$$s_{a,t}^{FFV} = \frac{H_t(1-\theta_t) - B_t^{FFV}(\theta_t - k)}{\gamma_a^{FFV}(B_t^{FFV}\xi + H_t\frac{2}{3})}\varsigma_a\lambda^4{}_t = \frac{B_t^{CV}(\theta_t - k)\varsigma_a\lambda^4{}_t}{\gamma_a^{FFV}(B_t^{FFV}\xi + H_t\frac{2}{3})} \geq \frac{B_t^{CV}(\theta_t - k)\varsigma_a\lambda^4{}_t}{\gamma_a^{CV}B_t^{CV}\xi} = \frac{(\theta_t - k)\varsigma_a\lambda^4{}_t}{\gamma_a^{CV}\xi} = t_{a,t}^{CV}$$

The second greater or equal sign holds because FFVs have lower fuel efficiency than CVs $\gamma_a^{FFV} < \gamma_a^{CV}$, while the energy equivalent fuel consumption $B_t^{FFV}\xi + H_t\frac{2}{3}$ by total FFV stock at current national level is way lower than $B_t^{CV}\xi$ of CV. Therefore, the inequality shows that the magnitude of the implicit subsidy imposed on FFVs is higher than the implicit tax on CVs.

Appendix B Table of Notation

Indexes	$t \in$ {t1 to T} time of year
	$i \in$ {CVS, FFV} vehicle type
	$a \in$ {a1 to a24} age group of vehicle stock
	$x \in$ {n, r} supply source either from domestic (n) or rest of the word (r)
Parameters	ξ: Energy efficient factor of preblended fuel
	ρ: Discount factor
	φ_i: Initial cost of the vehicle i ($/unit)
	η: Operational and management cost ($/mi)
	ε: Car annual registration fee ($/unit)
	κ: Actual blend rate of ethanol in RFS scenario
	γ_i: Fuel economy of vehicle I (mile/gge)
	ς_a: Mileage capacity per year per vehicle (mi/yr) at age a
	θ_t: Blend rate mandate in year t (%)
	v_a^0:initial vehicle stock of age a(unit)
	β: coefficient for market vehicle value depreciation
	π:depreciation rate due to wear and tear from aging
Variables	B^i_t: Blended fuel consumption by vehicle i in year t (gal/yr)
	E^s_t: Ethanol supply in year t (gal/yr)
	H_t: E100 consumed by FFV in year t(gal/yr)
	$G^{n,s}_t$: Gasoline supply in year t (gal/yr)
	$M^i_{a,t}$: Vehicle miles traveled or VMT by vehicle i at age *a* in year *t* (mile/yr)
	N^i_t: Number of newly purchased vehicle i in year t(unit)
	$R^i_{a,t}$: Number of early retired vehicle i at age *a* in year *t* (unit)
	$V^i_{a,t}$: Vehicle stock of vehicle i at age *a* in year *t* (unit)