Overlapping Strategies for Reducing Carbon Emissions from the Personal Transportation Sector[*]

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Abstract

We develop a numerical model to simulate the impacts of overlapping energy policies on carbon emissions in the U.S. personal transportation sector. Consumers in our model demand fuel based on their underlying demand for miles and choices about car fuel economy; firms supply fuel by blending gasoline with corn, sugarcane, and cellulosic ethanol. We find that the current fuel tax, size-based fuel-economy standard, and percent renewable fuel standard together lead to a 9% reduction in carbon emissions at an average surplus cost in the fuel market of $44/tCO2. A carbon tax, in contrast, costs just $15/tCO2, followed by a fuel tax, traditional fuel-economy standard, low-carbon fuel standard, size-based fuel economy standard, and renewable fuel quantity standard, all of which are less costly than the current policy mix. We also consider impacts on unpriced externalities associated with car size and miles traveled, e.g. external accident fatality risks and traffic congestion. We find that fuel-economy standards greatly exacerbate these externalities, while taxes on fuel and carbon mitigate them. Thus, fuel-economy standards have higher abatement costs even when consumers undervalue fuel economy, e.g. due to myopia.

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Introduction

Multiple federal and state policies aim to reduce greenhouse gas (GHG) emissions from light-duty vehicles: fuel economy or GHG emissions performance standards, ethanol subsidies, renewable fuel blending mandates, and, in California, a low-carbon fuel standard. To what extent can such policies substitute for taxes on gasoline or carbon? To what extent would they be useful complements?

To assess the performance of these multiple overlapping policies, we reformulate the two-stage electricity-sector model of Fischer, Newell, and Preonas (2013) and apply it to the personal transportation sector. Our model captures the supply of transportation fuels with differing carbon emission rates, including gasoline, corn-based ethanol, sugarcane ethanol, and cellulosic ethanol. Our model also captures the demand for transportation fuels, which derives from the underlying demand for miles and for fuel economy. While a carbon tax is a powerful tool in our modeling framework, it may not be sufficient to address all fuel-related market failures. In particular, cellulosic ethanol production is characterized by knowledge spillovers due to learning-by-doing, while consumers may undervalue improvements in fuel economy due to myopia or other behavioral biases (i.e., the "energy efficiency gap"). Thus, the optimal policy may in general include a carbon tax complemented by corrective subsidies (or mandates) for cellulosic ethanol production and for fuel-economy improvements. Moreover, there may be unpriced externalities related to vehicle size and miles traveled (e.g., accident risks and congestion) that are either exacerbated or ameliorated by the fuel-related policies we consider.

We parameterize our model based on EIA projections and estimates drawn from the empirical economics literature, and we use this parameterized model to simulate the impacts of various policies—or combinations thereof—on fuel prices, quantities, carbon emissions, and overall welfare. Our main parameterization assumes that consumers fully value fuel economy (see Anderson and Sallee 2016 for a review). We find in this case that the current mix of state and federal fuel taxes, fuel economy standards, and percent renewable fuel blending mandates leads to a 9% reduction in domestic carbon emissions from this sector at an average surplus cost in the fuel market of \$44/tCO2. These policies induce behavioral changes that are highly cost-ineffective, however, with a marginal cost of carbon abatement that varies widely across competing abatement options: $0/tCO2 to $736/tCO2 for fuel switching (e.g., from gasoline to ethanol) and $31/tCO2 to $73/tCO2 for fuel conservation (i.e., driving fewer miles or improving fuel economy).

In contrast, the optimal carbon policy—a carbon tax combined with a corrective subsidy for cellulosic ethanol production—achieves the same 9% reduction in carbon emissions at an average cost of $15.2/tCO2. Equilibrium production of cellulosic ethanol in this case is zero. Thus, in practice, the optimal carbon policy does not require an ethanol subsidy and is therefore equivalent to a stand-alone carbon tax. Meanwhile, since a carbon tax leads to very little corn ethanol production and zero sugarcane ethanol production, a straight fuel tax performs nearly as well, costing just $15.4/tCO2. Command-and-control policies are all more costly: traditional and size-based fuel-economy standards cost $20/tCO2 and $27/tCO2, while a low-carbon fuel standard and renewable fuel quantity standard cost $24/tCO2 and $28/tCO2.

After accounting for unpriced externalities associated with car size and miles traveled, the carbon tax delivers a welfare *gain* of $21/tCO2, since this policy leads both to smaller cars and to fewer miles traveled. Meanwhile, the straight fuel tax actually delivers a slightly larger welfare gain of $22/tCO2, as this policy must achieve *all* of its carbon abatement via smaller (and more efficient cars) cars driving fewer miles and none through fuel-switching. In contrast, the cost of the traditional fuel-economy standard increases to $26/tCO2, while the cost of the size-based standard, which leads to bigger cars driving more miles, balloons to $71/tCO2. Neither the cost of the low-carbon fuel standard nor the renewable fuel quantity standard are much affected by accounting for these other unpriced externalities, however, as neither policy leads to substantial changes in vehicle size or miles traveled.

To explore how consumer undervaluation of fuel economy might impact our results, we reparametrize our model, assuming that consumers perceive only 75% of the fuel savings from improved fuel economy (see Allcott and Wozny 2014). We find that abatement costs for policies targeting fuel conservation—namely, the optimal carbon policy (which now includes a corrective subsidy for improved fuel economy), carbon tax, fuel tax, and traditional and size-based fuel-economy standards—fall substantially, to the point that they all deliver net welfare gains. In fact, the traditional fuel-economy standard delivers bigger gains than either the fuel tax or carbon tax and comes close to the optimal carbon policy. In contrast, abatement costs for policies targeting fuel-switching—namely, the low-carbon fuel standard and renewable fuel standard—are largely unaffected. However, when we again consider impacts on unpriced externalities, welfare gains for the fuel tax and carbon tax rise substantially, while net costs for the size-based standard again increase substantially.

Overlapping environmental policies have been an increasing area of interest for researchers and policymakers in recent years. OECD (2011) conducted a comprehensive review of interactions between emissions trading systems and other instruments, following a review by the Congressional Budget Office (2009) on regulatory interactions with cap-and-trade programs. De Gorter and Just (2010) consider interactions between biofuel subsidies and mandates. Many studies are critical of overlapping policies as distorting the price signals of emissions trading and raising costs (e.g., Böhringer and Rosendahl 2010). Others focus on the extent to which other market failures can justify overlapping climate policies (e.g., Fischer and Preonas 2010, Fischer et al. 2013, and Fischer 2016), and how policies should adjust when some instruments are missing (Hübler et al. 2015). Finally, recent research has focused on comprehensively measuring the broad range of externalities associated with driving and energy consumption—beyond the greenhouse gas implications—across a wide range of countries (e.g., Davis 2016 and Parry et al. 2014).

Our paper is closely related to Fischer and Newell (2008), who assess different policies for reducing carbon emissions and promoting innovation and diffusion of renewable energy, with an application to the U.S. electricity sector. They show that the optimal policy involves a portfolio of different instruments targeting not only emissions, but also learning and R&D. Despite those spillovers, however, they find that the most cost-effective single policy for reducing emissions is a carbon tax, followed by (in descending order of cost-effectiveness) an emissions performance standard, a fossil power tax, a renewable electricity share mandate, a renewable electricity subsidy, and lastly an R&D subsidy. Fischer, Newell, and Preonas (2013) extend and update the model of Fischer and Newell (2008) in several important ways by distinguishing between conventional renewable energy sources (such as wind or biomass) and advanced technologies (such as solar), and by modeling energy efficiency improvements over time. They find weak support for renewable electricity subsidies, even in the presence of large learning or R&D spillovers. Meanwhile, policies to promote energy efficiency can be an important complement to the taxation of carbon emissions in the presence of systematic undervaluation of energy efficiency.

The rest of this paper proceeds as follows. In the next section (**Policy background**), we survey existing U.S. state and federal policies related to transportation fuels and automobile fuel economy. We then describe our model's theoretical structure (**Model**), what our model implies both for the optimal combination of policies and for understanding the current policy mix (**Policies**), and our numerical implementation of this model (**Numerical application**). We then discuss results based on our main parameterization (**Main results**) and results based on several alternative parameterizations of our model (**Alternative parameterizations)**, while the final section concludes (**Conclusion**).

Policy background

In this section, we survey existing U.S. state and federal policies related to transportation fuels and automobile fuel economy.

Carbon pricing and fuel taxes

The federal tax on motor gasoline is just $0.184 per gallon and has not increased since 1993. Since the tax is not indexed to inflation, it is constantly declining in real terms. Meanwhile, the sales-weighted average state gasoline tax was about $0.30 per gallon as of January 2016 (API 2016). This average fluctuates over time because many states impose a percentage tax on retail gasoline revenues rather than a fixed per-gallon tax, leading to fluctuations due to volatile energy prices. In addition, states are more active in raising taxes to keep up with inflation and to fund transportation infrastructure and other public programs. Since the inception of the federal gasoline tax in 1932, these taxes have largely been viewed as implicit charges on driving to fund roads, highways, and other transportation infrastructure, with little if any attention to the environmental benefits of taxing fuel on the part of state and federal policymakers.

Renewable Fuel Standard

The federal Renewable Fuel Standard (RFS) was first implemented by the Energy Policy Act of 2005 and was expanded soon thereafter by the Energy Independence and Security Act of 2007. The latter legislation calls for a minimum quantity of 36 billion gallons of renewable fuel per year by 2022, phased in gradually. This target can be satisfied with a wide range of renewable fuel technologies, including conventional corn-based ethanol. In addition, the policy sets separate nested minimum targets for different categories of biofuels, as depicted in Figure 1. These categories are cellulosic biofuel (which must be produced from cellulose, hemicellulose, or lignin and must meet a 60% lifecycle GHG reduction compared to a 2005 petroleum baseline); advanced biofuel (produced from qualifying renewable biomass other than corn starch and must meet a 50% GHG reduction target); biomass-based diesel (which must also meet a 50% lifecycle GHG reduction); and renewable fuel in general (which is effectively conventional ethanol derived from corn starch and which must meet a 20% lifecycle GHG reduction threshold) (EPA 2016).

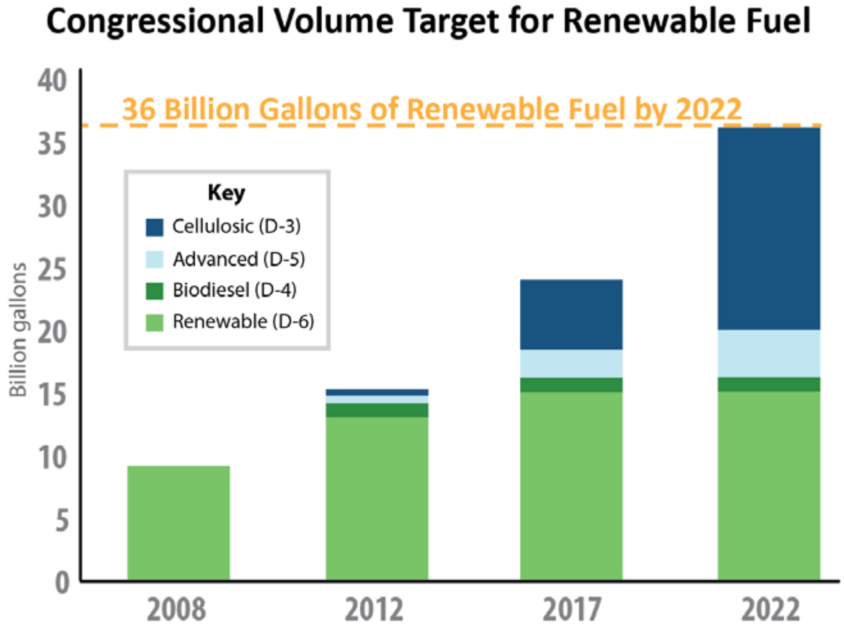

Figure 1: RFS Targets by Fuel Type (Source: EPA 2016)

In practice, the policy as implemented by EPA deviates from these legislated quantities in two critical ways. First, although legislated as a fixed minimum quantity, EPA implements the policy as tradable performance standard, whereby for every gallon of conventional petroleum-based fuel that is refined or imported for domestic consumption, a given quantity of renewable fuel (all types, advanced, and cellulosic) must also be blended into the domestic fuel supply; these per-gallon performance standards are chosen in advance of the relevant compliance period in an attempt to achieve the legislated quantity of renewable fuel, based on EIA forecasts for total fuel demand in the upcoming compliance period. Regulated entities that blend more renewable fuel than required by regulation earn extra credits (RINs) that they may sell to other entities who blend less than they are required. Thus, the policy acts as an implicit tax on conventional petroleum-based fuels, in addition to an implicit subsidy to renewable fuels, with RIN prices reflecting the size of the marginal tax and subsidy (as we discuss in detail below).

Second, the legislation grants EPA the discretion to reduce the stringency of the RFS if the cost of meeting the standard is excessive, or if there is insufficient renewable fuel production capacity to meet the standard. Indeed, capacity to supply cellulosic ethanol has significantly lagged the legislation's expectations, and so EPA has repeatedly revised downward the required target for cellulosic ethanol. Thus, the "current policy" baseline in our simulations reflects a significantly weakened target for cellulosic ethanol.

Low-carbon fuel standard (LCFS) for liquid transport fuels

California's Low Carbon Fuel Standard (LCFS) was created by executive order in 2007 and requires at least a 10% reduction in the carbon intensity of California's transportation fuels by 2020. Like the federal RFS, the policy is implemented as a tradable performance standard, which sets a maximum life-cycle carbon emissions per BTU for all transportation fuel sold in California. Under this policy, high-carbon fuels (i.e., those with emissions rates higher than the standard) are implicitly taxed, while low-carbon fuels (i.e., with emissions rates lower than the standard) receive an implicit subsidy. Thus, the LCFS is somewhat similar in structure to the federal RFS (as we further discuss below). Unlike the federal RFS, however, under which fuels are taxed or subsidized based on coarse fuel-type classifications, the magnitude of a fuel's implicit tax or subsidy under the LCFS is directly proportional to its life-cycle GHG emissions rate. Under California's LCFS, the emissions rate for each fuel production technology or "pathway" is assessed in a rigorous certification process. So, for example, one pathway might be dry-mill, corn-based ethanol, with process heat coming from natural gas, while another pathway might be dry-mill, corn-based ethanol, with process heat coming from coal. In our simulations, we consider a potential federal LCFS modeled on the California program.

Other biofuels incentives

Until recently, production of corn-based ethanol, cellulosic ethanol, and other biofuels was supported by a wide range of other state and federal subsidies. These included the federal

Volumetric Ethanol Excise Tax Credit, which in the years immediately preceding its removal provided a blending subsidy of $0.45 per gallon for all forms of ethanol, an ethanol import tariff of $0.54 per gallon (intended in part to counteract the ethanol blending subsidy, so that it benefitted mainly domestic producers),[1] a federal subsidy of $1.01 per gallon for the production of cellulosic ethanol, and similar subsidies in a range of other states. The federal ethanol subsidy and import tariff expired at the end of 2011, while the cellulosic ethanol subsidy was scheduled to end in December 2014 but was extended through 2016.[2] However, other incentives for biomass feedstock producers, excise and income tax relief, and other smaller programs remain. At the same time, several states also offer financial incentives to biofuels, although many subsidies have also ended.[3]

CAFE standards

Since the late 1970s, and following in the wake of the energy crisis, the Corporate Average Fuel Economy (CAFE) standards have set a minimum average fuel economy for the new light-duty vehicle fleet of each manufacturer. In the early years, there were uniform standards for passenger cars, and uniform standards for light trucks (e.g., minivans and SUVs) that applied equally to each manufacturer, with a limited ability for credit banking and borrowing across years, but no trading of credits across a manufacturer's passenger car and light truck fleets, and no trading across manufacturers. Over time, through a combination of new legislation and regulatory discretion, the program has evolved to one in which each manufacturer faces a different size-based standard: manufacturers that sell smaller vehicles face more stringent standards, while manufacturers that sell bigger vehicles face less stringent standards. Cars and trucks are still regulated under separate standards, but vehicles of the same size are treated roughly equally under both standards. Meanwhile, manufacturers are not only allowed to bank and borrow credits across years and with more flexibility, but they are also allowed to trade credits across their car and light

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[1] A small amount of ethanol was allowed to be imported tariff-free under the Caribbean Basin Initiative.

[2] See http://www.afdc.energy.gov/laws/10515

[3] See http://www.afdc.energy.gov/laws

truck fleets, as well as with other manufacturers.[4] Thus, in its current form, the policy generates an implicit subsidy for fuel economy conditional on size, which acts as an implicit subsidy for fuel economy combined with an implicit subsidy for vehicle size. Below, we model this size-based standard as directly regulating average vehicle fuel economy divided by average vehicle size, which approximates the incentives generated by the size-based CAFE standard.

Model

We model the supply and demand of transportation fuels in the light-duty vehicle (LDV) market—essentially, personal cars and trucks and blends of gasoline and ethanol. Although not all LDVs rely on gasoline, the vast majority in the United States do (99% in recent history, according to EIA 2015). Similarly, although not all gasoline is consumed by LDVs, they demand the largest share (roughly 90%).[5] Thus, a focus on gasoline offers a reasonable representation of the light-duty market and vice versa. The model itself is styled after the electricity sector model of Fischer, Newell, and Preonas (2013). It is deliberately simple so as to capture the key features of multiple interacting market failures over time, while remaining transparent. Details of the model equations are given in the Appendix, and we summarize the essential features in this section.

As a simplifying assumption, fuels from different sources are assumed to be perfect substitutes. These sources are distinguished both by different rates of carbon emissions and different innovation potential. We do not model the "blend wall" for ethanol usage in conventional gasoline engines, nor do we model demand for high-ethanol fuel blends (e.g., E85) by owners of flexible-fuel vehicles, or the gradual penetration of flexible-fuel vehicles and fueling infrastructure necessary to deliver high-ethanol blends. In ignoring these short-run frictions, we implicitly

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[4] In addition, whereas the Department of Transportation (DOT) was charged with regulating fuel economy, recent rulemakings are conducted jointly between the DOT and EPA, with a policy that is now aimed at regulating both fuel economy and GHG emissions per mile. Note that per-mile CO2 emissions due to fuel combustion are directly proportional to fuel efficiency. Thus, the distinction between regulating GHG and regulating fuel economy is slight, and comes from relatively minor non-CO2 related GHG emissions (e.g., leakage of air conditioning refrigerant).

[5] See http://www.eia.gov/energyexplained/index.cfm?page=gasoline_use

assume a medium- to long-run model in which there is sufficient time to make the necessary investments and adjustments, and we calibrate our model accordingly.[6]

The model has two stages: a first stage made up of n_1 years, representing the time it takes for innovation to occur, and a second stage of n_2 years, during which the fruits of that innovation accrue in the form of lower production costs. The time it takes the new vehicle fleet to turn over, and for capital investments in fuel supply and fueling infrastructure to occur, are also considerations in our choice of period length. Fuel supply, fuel economy improvements, and fuel consumption occur in both stages, while investment in knowledge only takes place during the first stage. An important assumption is that both consumers and producers take both current and future prices as given—there is no market power—having perfect foresight about those prices. In practice, this will only matter for producers of cellulosic ethanol, as we assume that production costs for other fuels are independent across stages and that consumer investments in fuel economy made during the first stage do not carry over to the second stage.

For simplicity, we assume that annual behavior within each stage is identical, and we report annual values for prices and quantities in each stage. For decisions involving tradeoffs between the two stages, we must account for time discounting. Accordingly, let δ_1 be the average discount factor for the n_1 years of stage 1 and δ_2 be the average discount factor for the n_2 years of stage 2; multiplication by these discount factors puts costs and benefits in present value terms to the first year of our $n_1 + n_2$ year time horizon.[7] Then the discount factor between stages—that is, the discount on annual costs and benefits in stage 2 relative to stage 1—is given by $\delta = \delta_2 / \delta_1$.

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[6] Anderson (2012) and Salvo and Huse (2013) show that demand for high-ethanol blends among owners of flexible-fuel vehicles in the U.S. Midwest and in Brazil is highly—albeit not perfectly—elastic with respect to relative fuel prices. These results are consistent with a high degree of substitutibility between the two fuels, assuming the proper infrastructure is in place. Pouliot and Babcock (2014a, 2014b) show that infrastructure constraints can severely limit ethanol adoption in the short run; they do not model medium or long-run demand that accounts for new infrastructure. Infrastructure costs and constraints are implicitly reflected in our baseline calibration, however, as we describe below.

[7] The relevant formulae are $\delta_1 = \left(1-(1+r)^{-n_1}\right)(1+r)/(rn_1)$ and $\delta_2 = \left(1-(1+r)^{-n_2}\right)(1+r)^{1-n_1}/(rn_2)$.

We consider the following policies targeting fuel consumption and production:[8]

- Carbon tax
- Fuel tax
- Renewable fuel quantity standard
- Renewable fuel percent share standard
- Low-carbon fuel standard
- Fuel economy standard
- Size-based fuel economy standard

Since each fuel source has a fixed emissions rate (i.e., we assume no abatement opportunities conditional on fuel type), the carbon tax acts like a set of fuel-specific taxes. Thus, we will model this policy as such. Likewise, the two versions of the renewable fuel standard and the low-carbon fuel standard also generate incentives that can be modeled as systems of fuel-specific taxes and/or subsidies, as we show in detail below. For now, let P_t be the retail price of gasoline blends and ϕ_t^i represent the net tax on fuel source *i* in equilibrium after accounting for all policy incentives, which may be either explicit or implicit. Similarly, the two types of fuel-economy standards generate incentives that can be modeled as subsidies for reductions in vehicle size and/or percent improvements in fuel economy conditional on size.

Fossil fuels

Gasoline derived from crude oil (denoted by *x*) is assumed to be produced with mature technologies that do not experience endogenous technological change. While innovation is ongoing in the oil extraction sector, those activities are assumed to be exogenous to the policies promoted in this market. Nor do we distinguish among upstream sources of crude oil for refining, although they may have different emissions characteristics, as our parameterization data do not differentiate gasoline supplies by source.[9]

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[8] In addition to the fuel-related policies we consider here, our model would also permit us to consider taxes on vehicle miles traveled and/or weight, to mitigate miles-related and weight-related externalities (e.g., congestion and accident fatality risks). Below, we quantify changes in these external damages due to the fuel-related policies we consider.

[9] A fuller representation would require incorporating multiple oil supply types and international trade in those types, and then modeling the compatability of refinery capacity with those different types. Our simplifying assumption primarily affects the LCFS, which differentiates between very specific fuel production pathways, and the carbon tax, depending on how the carbon tax might be implemented.

Profits from the fossil-fuel sector are described in (A.13). Gasoline production is assumed to have upward-sloping marginal costs ($C_t'^x(q_t^x)$), arising through a combination of increasing marginal costs for domestic refining and distribution, as well as the sensitivity of world crude oil and gasoline prices to changes in the quantity of U.S. gasoline consumption. In the competitive equilibrium with positive production, the marginal cost of gasoline production equals the price of fuel less the net tax on gasoline:

$$C_t'^x(q_t^x) = P_t - \phi_t^x \text{ for } t = \{1,2\}, \tag{1}$$

Renewable fuels

In comparison to conventional gasoline, renewable fuels have lower emissions factors, and cellulosic ethanol is expected to experience significant technological change. We consider two mature biofuels: a conventional ethanol distilled from corn (denoted *m* for "maize") and sugarcane ethanol imported from Brazil (denoted *b* for "Brazil"). We also consider cellulosic ethanol made from woody biomass, crop residues, or dedicated bioenergy feedstocks (denoted *w* for "woody biomass"). The different biofuel sources and production processes entail different emissions factors, which is important for calculating the emissions impacts of policies. In addition, some of the policies, such as a carbon tax or an LCFS, impose taxes or constraints that depend directly on these emissions factors. Our parameterization below implies that conventional gasoline is the most emissions-intensive fuel on an energy-adjusted basis, followed by corn-based ethanol, sugarcane ethanol, and cellulosic ethanol: $\mu^x > \mu^m > \mu^s > \mu^w > 0$, where μ^j is the carbon emissions rate for transportation fuel type *j*.

Mature biofuels

We assume that cost curves for corn-based and sugarcane ethanol are exogenous, as there is some evidence that cost reductions over the past decades are primarily attributed to yield improvements and scale returns, rather than significant technical change in the production process. We then have upward-sloping supply curves for corn-based and imported ethanol: $C_t'^i(q_t^i) > 0$ for

$i = \{m,s\}$. In practice, we can think of the import supply curve as the residual supply of Brazilian sugar cane ethanol to the United States after domestic Brazilian demand is served.[10]

Maximizing profits (described in (A.14)) with respect to output in each period means that marginal production cost is set equal to the fuel price less the net tax, assuming strictly positive production.

$$C_t'^{j}(q_t^j) = P_t - \phi_1^j \text{ for } j = \{m,s\} \text{ and } t = \{1,2\} \tag{2}$$

However, if marginal costs at zero production exceed the fuel price less then net tax, then production is optimally set to zero.

Cellulosic ethanol

Cellulosic ethanol is assumed to experience significant technological change and endogenous innovation. Production costs G_t^w decrease with the stock of knowledge K_t^w that grows with learning-by-doing (LBD). Marginal fuel production costs are increasing in production q_t^w and declining in the knowledge stock. LBD occurs through cumulative experience, or Q_t^w; i.e., $Q_2 = Q_1 + n_1 q_1$ in the second stage.

Let ρ be a factor reflecting the degree of appropriability of returns from knowledge investments. For example, $\rho = 1$ would reflect one extreme case with perfect appropriability and no knowledge spillovers, while $\rho = 0$ reflects the opposite extreme case of no private appropriability of knowledge investments. Similarly, $1-\rho$ reflects the degree of knowledge spillovers. This representation of aggregate appropriation as a share of the total benefits was formally derived in Fischer and Newell (2008). We assume that all knowledge is ultimately adopted, either by imitation or by licensing. Therefore, the spillover factor does not enter directly into the aggregate profit function, which reflects operating profits (see (A.15)). Licensing revenues also do not appear because they represent transfers among firms. However, the spillover factor does enter into the first-order conditions for learning, since it determines the share of future profit

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[10] Although the United States has recently been a net exporter of ethanol, the FAO projects that it will largely be a net importer after 2014 (FAO 2012 "Biofuels Chapter").

changes that can be appropriated by the representative innovator. These issues are further elaborated in the appendix of Fischer and Newell (2008).

In the second stage, no further learning occurs. Thus, in the competitive equilibrium, like the other fuels, the marginal cost of producing cellulosic ethanol equals to the fuel price less the net tax, assuming strictly positive production:

$$G_q^w(K_2^w, q_2^w) = P_2 - \phi_2, \tag{3}$$

where the lettered subscripts on *G* denote partial derivatives with respect to *K*, *q*, and *Q*.

In the first stage, however, there is a value to innovation. Thus, the cellulosic ethanol industry produces until the marginal cost of production equals the fuel price less the net tax and plus the appropriable contribution of marginal output to future cost reductions through learning-by-doing:

$$G_q^w(K_1^w, q_1^w) = P_1 - \phi_1^w - \delta\rho n_2 G_K^w(K_2^w, q_2^w) K_Q^w(Q_2^w) \tag{4}$$

Note that the final term in this equation is positive overall, since $G_K < 0$, assuming strictly positive production. Again, production is optimally set to zero if marginal costs at zero exceed the fuel price less the net tax (plus any marginal future cost reductions than can be appropriated, in the case of the first stage).

If knowledge appropriation is imperfect ($\rho < 1$), from a societal perspective, firms have insufficient incentive to engage in extra production for the purpose of learning by doing. Thus, a knowledge externality accompanies the emissions externality, and both can be affected by policies that target one or the other.

Consumer demand and fuel economy decisions

We model demand for motor fuels from LDVs, and the characteristics of this market require important modifications to the demand-side of the Fischer et al. (2013) model. Demand for fuel is derived from the optimization problem of a representative consumer (see (A.16)). She experiences utility $u_t(v_t)$ from energy services v_t, which in this case is vehicle miles traveled

(VMT), and she is indifferent to the fuel source.[11] Thus, in equilibrium, there will be a single per-BTU price for all transportation fuels. The quantity of energy consumed is $\psi_t v_t$, where ψ_t is the fuel consumption rate per VMT. The cost of energy services thus depends on both the retail fuel price and the fuel consumption rate.

The fuel consumption rate (or the inverse of miles traveled per unit of energy, i.e. fuel economy) is a function of investments in fuel economy in each stage. In addition, there are two dimensions of fuel economy improvements: those due to reductions in average vehicle size (as measured by weight), and those due to the addition of fuel-saving technology. This formulation allows us to separately consider rebound effects, factors affecting fuel-economy choices, behavioral responses to price changes, and policies that regulate either overall fuel economy or fuel economy conditional on vehicle size, as has recently been the trend in the United States and other countries (see Anderson and Sallee 2016). Specifically, we assume that in each stage the energy consumption rate per mile is given by $\psi_t = \psi_t^0 e^{-(\theta_t^r + \theta_t^s)}$, where ψ_t^0 is the baseline fuel consumption rate, and $\theta_t \equiv \theta_t^s + \theta_t^r$ is the percent change in fuel economy, which can be decomposed into changes resulting from decreases in size (θ_t^s) and from the addition of costly fuel-saving technologies, conditional on size (θ_t^r).

As a convenient simplifying approximation, we assume that the average fuel consumption rate is proportional to average size and define the corresponding constant of proportionality as the level of fuel-saving technology. That is, we assume that the fuel consumption rate is given by $\psi_t = r_t s_t$, where size is given by $s_t = s_t^0 e^{-\theta_t^s}$ and the level of fuel-saving technology is given by $r_t = r_t^0 e^{-\theta_t^r}$. Note then that $\psi_t^0 = r_t^0 s_t^0$. We assume that size-based CAFE standards directly mandate a maximum level of r_t, while uniform CAFE standards mandate a maximum level of ψ_t. Note

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[11] Note that *u* is money-metric utility to simplify the optimzation problem.

that these assumptions are roughly consistent with EIA data on vehicle fuel economy by and on EIA projections for how the market will respond to attribute-based CAFE policy.[12]

The costs of these two dimensions of fuel-economy improvements are $Z_t^s(\theta_t^s)$ and $Z_t^r(\theta_t^r)$, which we assume are increasing and convex. Since our baseline policy includes a size-based CAFE standard that sets a maximum rate of per-mile fuel consumption conditional on car size (i.e., that forces the addition of fuel-saving technologies), scenarios that tighten this constraint will cause θ_t^r to increase, while scenarios that relax this constraint will cause it to decrease.[13] Meanwhile, car size itself could either increase or decrease, depending on the scenario. Thus, the *net* percentage change in fuel economy, which is given by $\theta_t \equiv \theta_t^s + \theta_t^r$, could be either positive or negative.

We also allow for potential consumer undervaluation of fuel economy, e.g. due to myopia or lack of information about the benefits. Let β be the perceived fuel-economy valuation rate, assumed constant across periods. A value of $\beta = 1$ indicates full valuation of fuel economy, while a value of $\beta < 1$ indicates undervaluation—for whatever reason, the consumer does not expect to receive the full benefits of improved fuel economy.[14] As with the valuation rate for cellulosic ethanol learning, these fuel-economy valuation rates will reveal themselves in the first-order conditions but do not appear directly in the aggregate net utility function.

Finally, as we show below, fuel-economy standards function as implicit subsidies to percent improvements in fuel economy via reductions in size (θ^s) and/or through the addition of

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[12] In particular, scatter diagrams of the average fuel consumption rate versus average weight of different size classes of cars and trucks show that the relationship is well-approximated by a ray through the origin (so the fuel consumption is roughly proportional to size) and that the slope of this ray declines as size-based CAFE standards become more stringent over time (so that the standard can be viewed as forcing a reduction in the constant of proportionality).

[13] Technically, the current policy regulates fuel economy conditional on a car's footprint (average wheelbase x the distance between the two axles), such that weight reductions and/or changes in other car attributes are potential responses to regulation. Thus, we implicitly asume that weight and footprint are constrained to change proportionally with each other and that other performance attributes (e.g., acceleration) remain fixed.

[14] Estimated values for the degree of consumer undervluation have varied widely in the literature, from large undervaluation to significant overvaluation (Greene 2010). Meanwhile, consumer surveys indicate that carbuyers focus primarily on fuel savings accrued during the first three years after purchase (Greene et al. 2013), while economic studies based on engineering data imply that off-the-shelf vehicle techologties are available that can improve fuel economy at negative net costs (NRC 2015). For a review of recent, high-quality empirical studies testing for consumer undervaluation of fuel economy in car markets, see Anderson and Sallee (2016).

fuel-saving technologies (θ^r). Thus, for simplicity, we will here model these incentives as direct subsidies.

We assume functional forms for utility that lead to a constant-elasticity demand function, $D_t(P_t, \psi_t)$, derived in the Appendix (see (A.18)):

$$D_t = N_t \psi_t^{1-\varepsilon} P_t^{-\varepsilon} \tag{5}$$

where N is an exogenous demand growth parameter and $\varepsilon < 1$ represents a short-run elasticity of demand, as might be reflected in the rebound effect—essentially, the response in VMT to changes in the price of fuel, holding fuel economy fixed. The full response of fuel demand to the price of fuel within a stage will also include adjustments to fuel economy.

With this functional form, we find that energy expenditures, given efficiency levels, are $P_t D_t = N_t \psi_t^{1-\varepsilon} P_t^{1-\varepsilon}$, and $\partial\{P_t D_t\} / \partial P_t = (1-\varepsilon) D_t > 0$; i.e., price increases raise total expenditures.

Meanwhile, the consumer invests in fuel-economy improvements in each dimension in each stage until the marginal costs equal the perceived marginal benefits, including any implicit subsidies generated by fuel-economy standards:

$$Z_t^{s\prime}(\theta_t^s) = \beta_t P_t D_t + \sigma_t^s \tag{6}$$

$$Z_t^{r\prime}(\theta_t^r) = \beta_t P_t D_t + \sigma_t^r, \tag{7}$$

In other words, the representative consumer balances the marginal cost of improving fuel economy in each dimension with the perceived fuel savings of that period plus the implicit subsidy generated by fuel economy regulation. Those investments are increasing in fuel prices, overall demand, fuel-economy subsidies, and the valuation degree. Note that whereas uniform CAFE standards generate implicit subsidies to improve fuel economy via both mechanisms, the size-based standard only gives incentives to improve fuel economy by adding fuel-saving technology.

Also note that since $r_t = \psi_t / s_t$, the size-based standard gives an implicit subsidy to vehicle size, which perversely counteracts the incentive to reduce the fuel consumption rate.[15]

Welfare changes

In our partial equilibrium model, we define welfare as the change in *economic surplus* relative to baseline, which is simply the sum of the changes in consumer and producer surplus, the change in direct revenue transfers from taxes and subsidies, and the change in total other external damages due to changes in vehicle size and miles traveled. For reporting purposes, we will often parse these changes into the *private surplus change* associated directly with fuel production and consumption given by the first three terms, as well as the *other external costs* associated with vehicle size and miles traveled given by the last term. We summarize these components here and give details in the Appendix.

Private welfare change

The change in consumer surplus is calculated as the change in net utility, given in equation (A.16). Note that "expenditures" on fuel economy improvements can either be direct financial expenditures in terms of higher vehicle cost or the opportunity cost associated with forgone vehicle size. The change in producer surplus is the change in after-tax profits, given in equations (A.13)–(A.15).

We assume that any changes in government revenues are compensated by lump-sum transfers to consumers. The amount of these transfers equals total receipts from carbon and fuel taxes less subsidies to alternative fuels and fuel economy, given in (A.19). Of course, implicit taxes and subsidies due to command-and-control regulations—for example, the CAFE standards or the federal RFS—do not have direct government revenue implications, nor do they affect consumer

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[15] Ito and Sallee (2014) study fuel economy standards in Japan, where the fuel economy standards are a step function of vehicle weight, featuring large steps or "notches" such that small increases in weight can potentially lead to large reductions in a vehicle's required fuel economy under the standard. They find a significant increase in vehicle weight in response to the "notches" in this standard. While similar incentives to increase weight exist under the U.S. size-based standard, measuring automaker responses is difficult, since the size-based standard is a smooth function of size.

and producer surplus beyond their impacts on behavioral changes. Our choice to model these implicit taxes and subsidies as explicit does not alter our overall welfare calculations, since the taxes and subsidies are simply transfers.[16]

Greenhouse gas emissions

We assume climate damages are a function of cumulative, undiscounted emissions over both stages, where emissions in year *t* equal $E_t = \sum_{i=\{x,m,b,w\}} \mu^i q_t^i$. We will require all policy scenarios to meet the same emissions as the baseline, ensuring that the valuation of climate damages will not be a factor in our welfare comparisons.

Other external costs

While carbon emissions are held constant across our various scenarios, other outcomes associated with automobile-related externalities—notably vehicle size and miles traveled—are not. Indeed, an increase in driving may exacerbate local pollution, noise, congestion, and external fatality risks to pedestrians, cyclists, and other motorists, depending on where and when this extra driving occurs (Parry, Walls, and Harrington 2007).[17] Meanwhile, recent research has convincingly shown that heavier vehicles increase fatality risks to occupants in other vehicles (Anderson and Auffhammer 2014), which suggests that the damage caused by more driving would scale with vehicle size and vice versa. Ideally, these various externalities would be internalized through congestion pricing, more sophisticated pricing of accident insurance, and other first-best corrective policies. However, in the absence of such policies, the policies we consider to address fuel-related market failures will potentially have ancillary welfare impacts.

Accordingly, we define total other (i.e., non-carbon) external damages related to miles traveled and vehicle size as follows:

$$OD_t = d_v v_t + d_{vs} v_t (s_t - \overline{s}), \tag{8}$$

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[16] If and when we choose to focus on the distributional impacts of policies, however, then we will need to carefully parse these direct and indirect taxes and subsidies.

[17] Although local pollution is related to the level of fuel consumption and the content of fuel, vehicle emissions in the United States are regulated on a per-mile basis. Thus, in the economics literature, local pollution is typically modeled as scaling directly with miles traveled (Parry, Walls, and Harrington 2007), and we follow that convention here.

where d_v is the average marginal external damage associated with miles traveled, which includes local pollution, congestion, and fatality risks to motorcyclists and pedestrians that accrue even for the smallest cars (see Anderson and Auffhammer 2014), d_{vs} is the average marginal external damage associated with the interaction between miles traveled and vehicle size above a given minimum car size $\bar{s}$ (see Anderson and Auffhammer 2014), and v_t and s_t are total miles traveled and average car size, as above.

Equilibrium

In equilibrium, total fuel consumption must equal total production, the sum of fuel from all sources (i.e, $D_t = \sum_{i=\{x,m,b,w\}} q_t^i)$. In addition, all of the first-order conditions must hold, as must all of the policy constraints. Above, we alluded to the fact that the net taxes and subsidies would also include implicit taxes and subsidies generated by policy constraints. Below, we formally specify such constraints and derive the implicit taxes and subsidies that they generate.

CAFE constraints

We model two types of CAFE standards. Uniform CAFE standards (CAFE-TRAD) mandate a minimum average fuel economy on the vehicle fleet. Thus, for our representative consumer, this standard implies maximum per-mile fuel consumption rate in each stage. Formally, the constraint is

$$\bar{\psi}_t - \psi_t \geq 0 \text{ with } \lambda_t^{CAFE-TRAD} \geq 0 \text{ and } (\bar{\psi}_t - \psi_t)\lambda_t^{CAFE-TRAD} = 0. \tag{9}$$

where $\lambda_t^{CAFE-TRAD}$ is the shadow price on the constraint. To determine the implicit incentives given by this constraint, consider adding the shadow-price-weighted constraint to the Lagrangean for a consumer's constrained utility-maximization problem: $(\bar{\psi}_t - \psi_t)\lambda_t^{CAFE-TRAD}$. Differentiating with respect to percent improvements in fuel economy then yields the following implicit subsidy:

$$\sigma_t^{r,CAFE-TRAD} = \sigma_t^{s,CAFE-TRAD} = \frac{\partial[(\bar{\psi}_t - \psi_t)\lambda_t^{CAFE-TRAD}]}{\partial \theta_t} = \psi_t \lambda_t^{CAFE-TRAD}. \tag{10}$$

Note that this subsidy is identical for both improvements via reductions in size (θ^s) and via the addition of fuel-saving technologies conditional on size (θ^r).

We also model size-based CAFE standards (CAFE-SIZE). These standards impose a minimum average level of fuel economy that depends on size distribution of the vehicle fleet. In principle, regulated fuel economy could be any function of size. In practice, mandated fuel economy is roughly proportional to size. Thus, given our simplifying assumptions above, the standard imposes a maximum fuel consumption rate per VMT per size in each stage. That is, the constraint is given by

$$(\overline{r}_t - r_t)s_t \geq 0 \text{ with } \quad \lambda_t^{r,CAFE-SIZE} \geq 0 \text{ and } \quad (\overline{r} - r_t)s_t\lambda_t^{r,CAFE-SIZE} = 0,$$

where $\lambda_t^{CAFE-SIZE}$ is the shadow price on the constraint and note that we have scaled the constraint by vehicle size such that both the constraint and its shadow price have the same units as for the uniform CAFE standard above. To determine the implicit incentives given by this constraint, again consider adding the shadow-price-weighted constraint to the Lagrangean for the consumer's problem: $(\overline{r} - r_t)s_t\lambda_t^{r,CAFE-SIZE} = 0.$ Differentiating with respect to percent improvements in fuel economy via fuel-saving technology then yields the following implicit subsidy:

$$\sigma_t^{r,CAFE-SIZE} = \frac{\partial[(\overline{r}_t - r_t)s_t\lambda_t^{CAFE-SIZE}]}{\partial\theta_t^r} = \psi_t\lambda_t^{CAFE-SIZE}, \qquad (11)$$

while differentiating with respect to percent improvements via size reveals an implicit subsidy of precisely zero: $\sigma_t^{s,CAFE-SIZE} = 0.$

Note that, in practice, both the uniform and size-based CAFE standards apply only to new vehicles. However, as our stages represent roughly a vehicle lifetime or longer, and policy targets are set with goals for fuel economy of the vehicle stock in mind, we find this formulation to be a useful simplification that still captures the main effects of policy on fuel economy.

Renewable Fuel Standard

As described above (**Policy background**), the federal RFS mandates that a certain overall quantity (or share) of renewable fuels be blended in the final fuel mix. However, it also mandates additional specific targets for cellulosic and advanced biofuels.[18] For example, sugarcane ethanol

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[18] The legislation also sets a target for biomass-based diesel; however, we are restricting ourselves to the LDV gasoline market.

imported from Brazil counts toward both the overall mandate and the advanced renewable fuel mandate, while cellulosic ethanol contributes to the overall mandate, the advanced renewable fuel mandate, and the cellulosic ethanol mandate.

As such, there are three RFS constraints relevant for our analysis:

$$\begin{aligned}
&B_t^R - \overline{B}_t^R \geq 0 \text{ with } \quad \lambda_t^{RFS-R} \geq 0 \text{ and } \quad (B_t^R - \overline{B}_t^R)\lambda_t^{RFS-R} = 0, \text{ where } B_t^R \equiv \sum_{i=\{m,s,w\}} q_t^i; \\
&B_t^A - \overline{B}_t^A \geq 0 \text{ with } \quad \lambda_t^{RFS-A} \geq 0 \text{ and } \quad (B_t^A - \overline{B}_t^A)\lambda_t^{RFS-A} = 0, \text{ where } B_t^A \equiv \sum_{i=\{s,w\}} q_t^i; \\
&B_t^C - \overline{B}_t^C \geq 0 \text{ with } \quad \lambda_t^{RFS-C} \geq 0 \text{ and } \quad (B_t^C - \overline{B}_t^C)\lambda_t^{RFS-C} = 0, \text{ where } B_t^C \equiv q_t^w,
\end{aligned}$$

where $\overline{B}_t^R$, $\overline{B}_t^A$, and $\overline{B}_t^C$ are the mandated quantities of renewable, advanced, and cellulosic biofuels, and λ_t^{RFS-R}, λ_t^{RFS-A}, and λ_t^{RFS-C} are the corresponding shadow prices on these quantity constraints. The net result is a set of implicit subsidies to the production of each type of renewable fuel:

$$\begin{aligned}
&\sigma_t^{m,RFS} = \lambda_t^{RFS-R}; \\
&\sigma_t^{b,RFS} = \lambda_t^{RFS-R} + \lambda_t^{RFS-A}; \\
&\sigma_t^{w,RFS} = \lambda_t^{RFS-R} + \lambda_t^{RFS-A} + \lambda_t^{RFS-C},
\end{aligned}$$

The RFS policy is implemented through a decentralized credit-trading scheme, in which each regulated entity (e.g., an oil refiner or importer) is responsible for ensuring that a given quantity of renewable fuel is supplied for domestic consumption. Suppliers that sell renewable fuel for domestic consumption generate credits called Renewable Information Numbers (or RINs) that can be used to offset their own obligations, or that can be sold to other regulated entities. Thus, the implicit subsidies directly above reveal themselves as market prices on RINs for the three different categories of biofuels.

The federal RFS is legislated in terms of fixed minimum quantities for the different categories of renewable fuels, as specified above. If the RFS were to be implemented literally as quantity-based standard (call this policy RFS-Q), then obligations to produce renewable fuel would need to be allocated in lump-sum fashion to regulated entities (e.g., in proportion to historical gasoline sales) such that the sum of these obligations across all regulated entities equaled the fixed quantity targets as legislated by the RFS. The "value" of these obligations would be given by the quantity of obligations multiplied by their relevant market prices (i.e., RIN prices) and would represent a lump-sum transfer from regulated entities to producers of renewable fuels.

In practice, the RFS is implemented by EPA as a percentage-based performance standard (call this policy RFS-%), in which obligations to produce renewable fuel are allocated in proportion to the quantity of petroleum-based fuel (i.e., gasoline) that each regulated entity supplies for domestic consumption, with this percentage chosen in an attempt to achieve the overall quantity targets of the RFS. The mandated quantities are no longer fixed, but rather are given by the following expressions:

$$\begin{aligned} \overline{B}_t^R &= \alpha_t^{RFS-R} q_t^x; \\ \overline{B}_t^A &= \alpha_t^{RFS-A} q_t^x; \\ \overline{B}_t^C &= \alpha_t^{RFS-C} q_t^x, \end{aligned}$$

where α_t^{RFS-R}, α_t^{RFS-A}, and α_t^{RFS-C} are the quantities of all renewable fuels, advanced biofuels, and cellulosic biofuels required for every unit of gasoline supplied. Thus, in addition to the implicit subsidies for each category of biofuels above, which take the same form, this particular implementation of the RFS generates an implicit tax on gasoline sales, equal to

$$\tau_t^{x,RFS} = \alpha_t^{RFS-R} \lambda_t^{RFS-R} + \alpha_t^{RFS-A} \lambda_t^{RFS-A} + \alpha_t^{RFS-A} \lambda_t^{RFS-A}. \tag{12}$$

Note therefore that the performance standard version of the RFS policy (RFS-%) has different incentive implications than the pure quantity-based RFS policy (RFS-Q).

Low Carbon Fuel Standard

The LCFS imposes a maximum average carbon emissions rate for all transportation fuels. Whereas the percentage-based RFS is a form of portfolio standard, the LCFS functions like a tradable performance standard.[19] The LCFS can be written as follows:

$$\overline{\mu}_t D_t - E_t \geq 0 \text{ with } \lambda_t^{LCFS} \geq 0 \text{ and } (\overline{\mu}_t D_t - E_t)\lambda_t^{LCFS} = 0,$$

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[19] Fischer and Newell (2008) discuss these distinctions in greater depth.

where $\overline{\mu}_t$ is the maximum carbon emissions rate. Implemented in a credit trading program, subsidies to fuels with below-average carbon content are financed with taxes on fuels with above-average carbon content. Implicitly, this policy imposes a tax on the carbon content of fuel combined with a subsidy to all fuel sold, with the net tax on fuel *i* given by $\tau_t^{i,LCFS} = \lambda_t^{LCFS}(\mu^i - \overline{\mu}_t)$. Equivalently, one can write this system of taxes and subsidies as a generic tax on all transportation fuels equal to $\tau_t^{LCFS} = \lambda_t^{LCFS}(\mu^x - \overline{\mu}_t)$ combined with a renewable fuel subsidy equal to $\sigma_t^{i,LCFS} = \lambda_t^{LCFS}(\mu^x - \mu^i)$ for *i = {m,s,w}*. The average net fuel tax is zero by definition, although the average cost of fuel may rise due to a shift towards lower-carbon fuels that have higher marginal production costs (see Holland et al. 2008). Finally, note in our model that one could replicate the same incentives as the LCFS by judiciously choosing the blend ratios of a percentage-based RFS, assuming that the LCFS in question implicitly taxes gasoline while implicitly subsidizing the three renewable fuels.[20]

Policies

In the presence of multiple market failures, multiple policy tools are required. Understanding these optimal policy combinations is useful for evaluating current, suboptimal policy combinations as well, as they indicate the relative importance and magnitude of the different components.

Optimal combination of policies

In the social optimum, the planner would maximize welfare subject to meeting the target level of carbon emissions. Implemented in a decentralized framework, the planner would create policy wedges to align the private first-order conditions with those from maximizing social welfare. The resulting conditions are:

1. A carbon price to address the corresponding GHG emissions externality, rising according to the discount factor: $\tau_1^{GHG} = \delta\tau_t^{GHG}$.
2. A subsidy to percent improvements in fuel economy in each stage, equal to the portion of fuel expenditures that goes undervalued by consumers: $\sigma_t^{\theta} = (1-\beta)P_tD_t$.

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[20] We have sketched out a proof that will eventually go here.

3. A subsidy for first-stage cellulosic ethanol production to address spillovers LBD knowledge generation: $\sigma_1^{w,LBD} = -\delta(1-\rho)n_2 G_K^w(K_2^w, q_2^w)K_Q^w(Q_2^w)$.

Thus, all fuels are taxed in proportion to their carbon emissions, while cellulosic ethanol benefits from an additional subsidy in the first stage to address LBD externalities—potentially but not necessarily leading to a net subsidy in this stage—and fuel-economy improvements via either mechanism are subsidized to address consumer undervaluation.

In the presence of other unpriced externalities associated with vehicle size and miles traveled, then in principle the following corrective policies could also be added:

4. A tax on miles traveled to address externalities related to pollution, noise, congestion, and external accident risk that is unrelated to weight: $\tau_t^{vmt} = d_v$.
5. A weight-differentiated tax on miles traveled to address the external accident risk that scales both with miles and weight: $\tau_t^{vs}(s_t - \overline{s})$ with $\tau_t^{vs} = d_{vs}$, where recall that $\overline{s}$ is the reference car size.

However, uniform taxes on miles and/or weight would only crudely address externalities associated with local pollution, noise, congestion, and external accident risks, which vary greatly over time and space. Thus, we prefer to focus on correcting market failures in fuel production and consumption, while separately keeping track of how the policies we consider might ameliorate or exacerbate externalities associated vehicle size and miles traveled.

Baseline combination of policies

In practice, of course, policy makers use a combination of mandates (and subsidies) to achieve their goals. In our numerical application below, we will consider a baseline in which fuel taxes, a percentage-based RFS (RFS-%), and size-based CAFE standards (CAFE-SIZE) all hold simultaneously. Thus, the net taxes on fuel in the baseline are given by the following:

$$\phi_t^{x,Baseline} = \tau_t^{Fuel} - \tau_t^{x,RFS}, \quad t = \{1,2\};$$
$$\phi_t^{m,Baseline} = \tau_t^{Fuel} + \sigma_t^{m,RFS}, \quad t = \{1,2\};$$
$$\phi_t^{s,Baseline} = \tau_t^{Fuel} + \sigma_t^{s,RFS}, \quad t = \{1,2\};$$
$$\phi_t^{b,Baseline} = \tau_t^{Fuel} + \sigma_t^{b,RFS}, \quad t = \{1,2\},$$

where τ_t^{Fuel} is the combined state and federal fuel tax in the baseline, and the baseline implicit taxes associated with the federal RFS are revealed by RIN prices.[21] In addition, we have net subsidies to fuel-economy improvements via technology given by:

$$\sigma_t^{r,Baseline} = \psi_t \lambda_t^{CAFE-SIZE},$$

where this baseline implicit subsidy is revealed by the gap between the marginal cost and marginal benefit of fuel-economy improvements via size.

Thus, we will be using our model to measure the net impacts of these baseline policies, along with welfare changes associated with alternative combinations of policies that achieve the same level of target carbon emissions.

Numerical application

In this section we describe our numerical implementation of this model. The functional forms for fuel production and knowledge follow those of Fischer, Newell, and Preonas (2013) unless otherwise noted. Details are given in the Appendix and we summarize the key features here.

The model assumes linear fuel supply curves for each fuel source. For advanced biofuels, the quadratic cost function is inversely related to the knowledge stock, so that technological change lowers both the intercept and the slope of the renewable fuel's supply curve. The relationship between the knowledge stock and cumulative experience takes a constant elasticity form, as is common in this literature: $K_2\left(Q_2\right)=\left(Q_2/Q_1\right)^k$, implying that $K_1=1$. Baseline marginal costs are drawn from the first-order conditions, evaluated at the baseline policy values and quantities.

Similarly, we assume a linear marginal cost for percent change improvements in fuel economy around the baseline. With baseline improvements normalized to zero, baseline marginal costs can be derived from the first-order conditions for fuel economy improvements, evaluated at baseline energy expenditures and shadow values of the CAFE constraints.

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[21] We do not explicitly model California's existing state-level LCFS, although it should be noted that changes in federal RFS (and other federal policies) could impact the cost of complying with California's LCFS and vice versa.

We parameterize this model using a combination of modeling assumptions and simulation forecasts based on EIA's National Energy Modeling System (NEMS) energy market simulation model, along with supplemental estimates from the economics literature, as described below.

We calibrate baseline values for fuel prices, quantities, marginal costs, and taxes and subsidies—including implicit taxes and subsidies generated by the RFS—to match average annual values for the "Reference" scenario in the EIA's Annual Energy Outlook (AEO) 2014, which is based on NEMS forecasts. In addition to published modeling results contained in AEO 2014, we rely heavily on extensive ancillary modeling results for AEO 2014 provided with the NEMS source code.[22] We choose stage 1 values by averaging over the years 2015-2024 and stage 2 values by averaging over the years 2025-2040. Thus, the length of stage 1 is 10 years, while the length of stage 2 is 16 years. These time periods collectively cover the full range of AEO projections and individually are long enough to allow for substantial expansion of renewable fuel production capacity and turnover of the light-duty vehicle stock.

We set the retail fuel price in each stage to match the projected retail price for motor gasoline.[23] Consistent with our model, we assume the same per-BTU retail price for all fuels.[24] We set the fuel tax to match EIA's combined state and federal tax for motor gasoline, which falls slightly from stage 1 to stage 2 due to EIA's assumption that federal taxes will remain constant in

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[22] Published AEO 2014 results are available here: http://www.eia.gov/forecasts/aeo/. Information on obtaining the source code and ancillary results can be found here: http://www.eia.gov/forecasts/aeo/info_nems_archive.cfm.

[23] While fuel quantities are typically reported both in BTUs and volumes (i.e., gallons or barrels), fuel prices are often reported on a per-volume basis. Thus, whenever necessary, we convert between per-gallon and per-BTU values using AEO 2014 projections for the BTU content of different fuel types over the relevant time ranges. Pure ethanol always has the same BTU content over time, as does gasoline. The BTU content of "motor gasoline" varies slightly over time, due to changes in the ethanol content of blended gasoline.

[24] This assumption is also consistent with EIA projections for retail gasoline and E85 prices, which, though fluctuating somewhat over time in EIA's projections, are very close to gasoline prices on an energy-adjusted basis.

nominal terms and therefore fall in real terms, due to inflation. We assume that this fuel tax applies equally to each fuel type on a per-BTU basis.[25]

Consistent with EIA forecasts, we assume a binding federal RFS in the baseline that takes the form of a percentage-based performance standard for different categories of renewable fuel, and we set the levels of the RFS targets to match the baseline renewable fuel blending shares. As noted above, these targets are lower than what is nominally required by legislation, reflecting EPA's ability to grant waivers in the face of excessive costs or insufficient production capacity for renewable fuels—a process that is explicitly modeled in NEMS forecasts. We calculate implicit subsidies for each category of renewable fuel from EIA projections for RIN credit prices, and we calculate the implicit tax on gasoline as the weighted average of these implicit subsidies, consistent with our derivations in (12).[26]

We use these retail prices, taxes, and implicit taxes and subsidies in combination with first-order conditions for production to solve for the implied marginal cost for each fuel type in the baseline. In the case of cellulosic ethanol in stage 1, this marginal cost is adjusted upward to account for the learning benefits that accrue in stage 2, as shown in (4). Note that EIA assumes ethanol producers are myopic both with respect to the future price of ethanol and with respect to the cost reductions associated with learning. Thus, our baseline calibration implies somewhat higher direct marginal production costs than is assumed by EIA.

To calibrate the slopes of our gasoline supply curves, we consider, in addition to the EIA's main "Reference" scenario, the "Extended Policy," "Low VMT," and "High VMT" scenarios, which respectively model an extension of CAFE standards to nearly 58 miles per gallon by 2040,

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[25] While EIA projections apparently assume the motor fuel tax applies equally to each fuel type on a per-gallon basis, the difference is relatively minor for fuel blends containing a small share of ethanol (e.g., E10 or E15). In addition, our assumption is consistent with the historical motivation for the gasoline tax as a rough "per mile" fee on driving to fund state and federal highway infrastructure projects.

[26] We were unable to find documentation explicitly describing the mathematical form of the federal RFS modeled in EIA projections. However, EIA tables that show the components of retail gasoline prices include an "RFS component" that is added on top of the wholesale price and that is closely approximated by the share-weighted average of the implicit shadow prices for the three categories of renewable fuel. Thus, the EIA projections are consistent with EPA's implementation of the RFS as a percentage-based performance standard.

relatively low growth in the demand for miles, and relatively high growth in the demand for miles. These shifts in U.S. demand for transportation fuels lead to four different price-quantity pairs, which we use to calibrate the slope of the (residual) supply curve for gasoline.[27] Meanwhile, we calibrate the slopes for corn, sugarcane, and cellulosic ethanol supply based on underlying EIA assumptions for the slopes of the supply curves for the requisite feedstocks.

We choose life-cycle emissions intensities for each fuel type based on NEMS modeling assumptions, which are themselves based on California Air Resources Board (CARB) assumptions used for implementation of California's LCFS.[28]

We calibrated k based on EIA NEMS assumptions for the rate at which capital costs for cellulosic ethanol decline as a function of cumulative capacity, which imply an elasticity of about 0.30.[29] However, our learning parameter applies to all costs, not just capital costs, and EIA NEMS assumptions imply that capital accounts for roughly half of total costs. Thus, we assume an overall learning parameter of $k = 0.15$, which coincidentally happens to be the learning parameter chosen by Fischer and Newell (2008). We also retain Fischer and Newell's (2008) assumed knowledge appropriability rate for cellulosic ethanol of $\rho = 0.5$ in our baseline and other central scenarios.

We calibrate the slopes and intercepts for the marginal cost curves for fuel economy under the assumption that consumers can freely choose the size of their cars, but that there is a binding size-based CAFE standard that fixes the ratio of fuel consumption per mile and vehicle size. For fuel economy improvements via reductions in vehicle size, our calibration is based on the first-order conditions (6) and (7). Note that this first-order condition directly relates the marginal cost of fuel economy improvements via size reductions to annual fuel expenditures. Thus, the intercept of this marginal cost curve (i.e., marginal costs in the baseline) is pinned down by baseline fuel expenditures, deflated by the degree of consumer undervaluation. To calibrate the slope, we consider, in addition EIA's main "Reference" scenario, the "Low oil price" scenario and "High oil

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[27] The residual supply in response to a higher domestic price potentially comes from two sources: higher domestic production and higher net imports (i.e., rest-of-the-world supply minus rest-of-the-world demand).

[28] These values are reported on page 81 of the "Liquid Fuels Market Module of the National Energy Modeling System: Model Documentation 2014," August 2014, available here: http://www.eia.gov/forecasts/aeo/nems/documentation/

[29] These values are reported on page 147 of the "Assumptions to the Annual Energy Outlook 2014," June 2014, available here: http://www.eia.gov/forecasts/aeo/assumptions/

price" scenario, which model the effects of lower or higher oil demand from non-OECD countries, along with higher or lower global supply. To calibrate the slope, we correlate changes in total fuel expenditures across these three different scenarios with corresponding percent changes in new-vehicle fuel economy, which by our assumption of a binding size-based CAFE standard must be coming from changes in vehicle size.

For fuel economy improvements conditional on size, a similar approach based on the consumer's first-order conditions will not work, given our assumption of a binding size-based CAFE standard. Instead, we directly examine the relationship between average new light-duty vehicle costs and average fuel consumption (divided by average size) over time, as the size-based CAFE standard increases in stringency in both the "Reference" scenario and "Extended policies" scenario. In particular, we correlate the average change in new-vehicle costs with the percent change in average fuel consumption. This relationship is well-approximated by a convex quadratic function, implying an upward-sloping marginal cost curve for percent improvements in fuel economy. To convert this average per-vehicle value to a sector-wide cost, we multiply by the stock of light duty vehicles. To convert this up-front investment cost to an annualized cost, we multiply by the interest rate plus depreciation rate.[30,31]

We rely on an extensive empirical literature that estimates short-run price elasticities of gasoline demand and miles traveled. We assume a short-run demand elasticity of $\varepsilon = 0.10$, based on numerous empirical studies.[32] As noted above, the long-run elasticity will be somewhat larger, as consumers re-optimize vehicle fuel economy. For the consumer fuel economy valuation factor,

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[30] For the annual interest rate, we choose a value of 5%, which is consistent with our assumed discount rate between stages. For the depreciation rate, we divide annual new vehicle sales in EIA projections by the stock of new vehicles, which implies an annual vehicle replacement rate of 6.3%-6.6%. We also consider that older vehicles are driven significantly fewer miles every year than new cars. Conditional on not being scrapped, this decay in miles is about 4% per year. Thus, we assume an effective annual depreciation rate of 10%-11%.

[31] We find that the implied marginal cost intercept in stage 1 is somewhat less than the marginal value of improving fuel economy in stage 1, based on total fuel expenditures. Thus, we reset the stage 1 intercept to match the total perceived benefit of a percent improvement in fuel economy in stage 1, implying a non-binding size-based standard.

[32] For example, Small and Van Dender (2007) and Gillingham et al. (2014) both estimate short-run price elasticities of -0.1 for miles traveled. For a recent review, including citations for other recent empirical studies, reviews, and meta-studies, see Anderson and Sallee (2016).

we initially assume β = 1.0, i.e. no undervaluation, and we subsequently conduct sensitivity analysis assuming β = 0.75.[33]

We set exogenous demand growth to 11% (i.e., $N_2 / N_1 = 20,595/18,479 = 1.11$, used in (5)) based on EIA's projected fuel prices and production, annualized across each stage; these demand scalars reflect exogenous trends in demand for vehicle miles traveled due to changing incomes and other demographics. As noted above, we calibrate stage 1 values based on annual averages for 2015-2024 and stage 2 values based on annual averages for 2025-2040. To ensure proper discounting of future costs and benefits, we must account for discounting both within and between stages the two stages of our model. At a 5% annual discount rate, the average discount on the $n_1 = 10$ years of stage 1 is $\delta_1 = 0.8108$, while the average discount on the $n_2 = 16$ years of stage 2 is $\delta_1 = 0.4366$, so that the discount factor between stages is $\delta = \delta_2 / \delta_1 = 0.5385$.

Table 1 shows the parameters associated with fuel cost functions and fuel economy investment functions. Note that Table 2 lists the other parameters that do not vary over time, including CO2 emissions intensity, knowledge appropriation rates, and short-run demand elasticities. Intercepts for all of our cost functions are defined relative to baseline production quantities, which reflect binding RFS and size-based CAFE constraints. Thus, we report these values in Table 3 in the next section, along with baseline fuel prices, quantities, policy constraints, and shadow values.

Main results

In this section we discuss results based on our main calibration. We begin by discussing the baseline combination of policies and the behaviors they induce in some detail. We then simulate a number of alternative policies—a counterfactual "no policy" baseline, as well as the optimal combination for addressing fuel-related market failures, along with a number of alternative policies that lead to the same level of carbon emissions as the baseline policy—systematically comparing the effects of these policies to the baseline and to each other. Finally, we use our model

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[33] The former assumption aligns with recent high-quality empirical studies that find no undervaluation (Busse et al. 2013; Sallee, West, & Fan 2015), while the latter assumption aligns more closely with recent high-quality studies that suggest modest undervaluation (Allcott 2013; Allcott & Wozny 2014). See Anderson and Sallee (2016) for a review.

to generate second-best marginal abatement cost curves, facilitating a graphical comparison of the policies.

Baseline policy

Table 3 reports the baseline retail prices, the fuel production quantities and marginal production costs for each fuel type, the miles traveled and vehicle attributes demanded by consumers (average size and fuel efficiency), and finally the values of the baseline policies and, in the case of binding quantity constraints, their baseline shadow values.

Several facts immediately jump out. First, note that while the marginal cost of gasoline is below the retail price (due to fuel taxation), the marginal cost of corn ethanol, sugarcane ethanol, and cellulosic ethanol all exceed the retail price (due to implicit subsidies for renewable fuel coming from the RFS targets). Thus, these renewable fuels are being produced at a marginal cost that greatly exceeds the marginal value of the energy they provide, which implies a *negative* cost for reducing carbon dioxide emissions by reducing reliance on these renewable fuels. This observation highlights the perverse incentives generated by policies like the RFS, LCFS, or other performance standards that do not fully price all of the carbon emissions associated with consuming each fuel type. Second, while the baseline marginal costs of corn ethanol and sugarcane ethanol are nearly identical, the life-cycle carbon emissions for corn are significantly greater, which suggests that the same level of carbon abatement could be obtained at significantly lower cost by relying more heavily on sugarcane ethanol and less heavily on corn ethanol. This observation highlights the inferior incentives generated by the RFS relative to the LCFS (or a carbon tax). Whereas the LCFS implicitly taxes or subsidizes fuels in proportion to their carbon emissions, the RFS implicitly taxes or subsidizes fuels according to categories that are only loosely tied to carbon emissions rates. Lastly, the table shows that the marginal cost of improving fuel economy via fuel-saving technology exceeds the marginal cost of improving fuel economy by reducing vehicle size, which reflects the binding size-based fuel economy standard in stage 2. Thus, the same level of fuel economy could be achieved at a lower cost by relaxing the size-based standard and re-introducing a uniform fuel economy standard.

Tables 4 and 5 examine these issues more systematically by calculating the marginal carbon abatement costs (at the baseline equilibrium) for different hypothetical abatement strategies in stage 1 and stage 2, respectively. Panel A of each table calculates marginal abatement costs for different "fuel substitution" strategies that involve decreasing production of a relatively high-carbon fuel and increasing production of a relatively low-carbon fuel. As shown in tables, the baseline combination of policies induces marginal abatement costs that vary widely across different such strategies, ranging from \$0.2/tCO2 for a strategy of replacing corn ethanol with sugarcane ethanol to \$410-\$736 per tCO2 for a strategy of replacing gasoline with corn ethanol.

Panel B of each table then calculates marginal abatement costs for different "fuel conservation" policies, both under the assumption that such conservation reduces only gasoline production, as well as under the assumption that such conservation reduces production of all fuels in proportion to their baseline production. As shown in the table, driving fewer miles is a relatively low-cost abatement strategy, especially when compared to most of the fuel-substitution strategies shown in Panel A. Costs are lower when it is assumed that this conservation decreases the production of all fuel types proportionally, since marginal production costs for all three types of renewable fuel exceed the baseline retail fuel price (i.e., their marginal value to consumers). The marginal abatement cost of driving smaller cars in both stages is the same as the cost of driving less, since the size-based fuel economy standard provides no incentive to reduce car size beyond the private fuel savings, which consumers fully value. Likewise, adding fuel-saving technology to cars in stage 1 has the same cost as driving less, since the baseline calibration implies a non-binding fuel-economy standard. Meanwhile, the binding size-based standard in stage 2 drives up the marginal cost of abatement via fuel-saving technology to about \$70/tCO2.

Alternative policy combinations

Overall, the above results imply significant inefficiencies in the current set of policies aimed at reducing carbon emissions from the personal transportation sector. In this section, we therefore consider alternative policy combinations, starting with the "no policy" counterfactual and then the optimal (i.e., private welfare-maximizing) combination of policies targeting fuel-related market failures—but ignoring other damages from vehicle size and miles traveled. In each of these subsequent comparisons—except for the "no policy" scenario—we require each policy to meet the same cumulative emissions as the baseline policy. Where relevant, we assume that carbon taxes, fuel taxes, the shadow price on the LCFS constraint, implicit renewable fuel subsidies under the quantity-based RFS, and implicit subsidies to fuel economy improvements under CAFE standards all grow at the between-period discount rate (ρ), which is consistent with policies that tax or regulate cumulative performance over time (or equivalently, that allow trading of compliance credits over time without penalty). In each case, we report welfare impacts and other outcomes in relation to the baseline values; we also report average abatement costs relative to the no-policy scenario. We initially focus on changes in private welfare in the fuels market and then return later to discuss the implications of accounting for other external damages. Table 6 reports the results of these simulations for our main calibration.

No-policy scenario

Column (1) of Table 6 presents the results of the "no-policy" scenario in which we turn off all policies, including state and federal fuel taxes. Relative to the baseline policy in column (2), cumulative CO2 emissions increase by 3.37 billion tons to 38.42 billion tons, while discounted private surplus in the fuel market increases by $147 billion. As the second-to-last row of the table shows, these changes in welfare and emissions imply that the baseline policy has an average carbon abatement cost of 147/3.37 = $43.7/tCO2.

Optimal policy combination

Column (3) presents results for the optimal carbon policy, which combines a carbon tax with an optimal corrective subsidy for learning-by-doing in cellulosic ethanol (and, in the presence of consumer undervaluation, an optimal corrective subsidy to fuel economy improvements). Given our parameterization, however, the equilibrium production of cellulosic ethanol is zero, such that the optimal subsidy to cellulosic ethanol is also zero. Thus, the optimal carbon policy in this case is equivalent to a stand-alone carbon tax. This policy leads to a discounted private surplus gain of $96 billion relative to the baseline policy. Thus, relative to the no-policy scenario, the optimal carbon policy has an average carbon abatement cost of $15.2/tCO2.

Individual policies

Column (4) presents results for the carbon tax, which leads to a private surplus gain of $96 billion relative to the baseline policy and has an average carbon abatement cost of $15.2/tCO2 (same as the optimal carbon policy). Meanwhile, column (5) presents results for the fuel tax, which leads to a surplus gain of $95.5 billion relative to the baseline policy and has an average carbon abatement cost of $15.4/tCO2.

Column (6) presents results for the low-carbon fuel standard, which leads to a private surplus gain of $66.9 billion relative to the baseline policy and has an average carbon abatement cost of $23.8/tCO2. Note that the LCFS does not raise retail fuel prices by nearly as much as the carbon tax or fuel tax. Thus, unlike these other policies, it largely fails to induce low-cost abatement via improved fuel economy and reductions in miles traveled.

Column (7) considers a quantity-based RFS in which the quantity targets are chosen precisely such that the *relative* subsidies for corn-based ethanol, sugarcane ethanol, and cellulosic ethanol versus gasoline are the same as under the LCFS.[34] Thus, the key difference is that the LCFS implicitly taxes gasoline, whereas the quantity-based RFS does not. Again, note that a percentage-based RFS that delivers the same *relative* subsidies across fuel types as the LCFS is, in equilibrium, the same as the LCFS itself. Our version of a quantity-based RFS leads to a private surplus gain of $52.8 billion relative to the baseline policy and has an average carbon abatement cost of $28.0/tCO2, making it the most costly individual policy that we consider.

Column (8) presents results for a uniform CAFE standard, which leads to a private surplus gain $79.7 billion relative to the baseline policy and has an average carbon abatement cost of negative $20.0/tCO2. Finally, column (9) presents results for the size-based CAFE standard, which leads to a surplus gain of $57.6 billion relative to the baseline policy and has an average carbon abatement cost of negative $26.6/tCO2. This policy is more costly that a traditional fuel-economy standard because it only subsidizes fuel economy improvements via technology and fails to subsidize potentially low-cost abatement via reductions in vehicle size.

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[34] That is, the implicit subsidy for ethanol type *i* takes the form $\sigma(\mu^x - \mu^i)$, where σ is the same across all three ethanol types. Of course, we implement this policy by directly subsidizing production of renewable fuels in proportion to their emissions rates relative to gasoline, choosing the overall subsidy rate to achieve the desired emissions target.

Second-best marginal abatement cost curves

Figure 2 presents second-best marginal abatement cost curves for these policies, illustrating their relative performance as we attempt to abate ever more carbon emissions; the figure note explains in detail how we calculated these curves.

Observe that the marginal abatement cost curve for the optimal policy coincides with that of the carbon tax; these policies remain equivalent over the full range of carbon abatement that we consider, since equilibrium cellulosic ethanol production remains zero. The fuel tax performs nearly as well up to about 7 billion tons of abatement, at which point the carbon tax begins to stimulate substitution toward renewable fuels at a substantially lower abatement cost than the fuel tax is able to deliver by fuel conservation alone.

Meanwhile, marginal costs for the size-based CAFE are initially comparable to the uniform CAFE standard. But these marginal costs quickly increase, immediately exceeding those of the uniform CAFE standard and exceeding those of the carbon tax and fuel tax at all levels of abatement.

The LCFS, which implicitly taxes high-carbon fuels while subsidizing low-carbon fuels, does not directly increase fuel prices like the fuel tax or carbon tax. Thus, this policy mainly encourages substitution toward renewable fuels and does little to encourage potentially low-cost fuel conservation. Its marginal costs exceed those of the preceding policies, with the exception of the size-based CAFE standard at low levels of abatement. Meanwhile, the quantity-based RFS only subsidizes renewable fuels without simultaneously taxing gasoline. Thus, this policy leads to a net *decrease* in fuel prices, which discourages low-cost fuel conservation. Thus, it has the highest marginal abatement costs.

Accounting for other external damages

Returning now to the bottom of Table 6, we calculate changes in other damages associated with changes in vehicle size and miles traveled, which we then subtract from the change in discounted private surplus to yield discounted private surplus less damages. We then calculate average costs per ton of abatement relative to the no-policy scenario, which we can compare to average abatement costs when ignoring other external damages.

By raising fuel prices, the baseline policy leads to somewhat smaller cars and fewer miles traveled than the no-policy scenario, which reduces its implied average carbon abatement costs by about a third. Since neither the LCFS nor the RFS have much impact on fuel prices, however, they lead to neither substantial changes in vehicle size nor substantial changes in miles traveled. Thus, their abatement costs are largely unchanged. Meanwhile, the uniform CAFE standard leads to more driving, but also to smaller cars, and these effects tend to cancel. Thus, average abatement costs increase only about a quarter.

As the bottom of Table 6 demonstrates, however, accounting for other external damages dramatically changes our assessment of the other four policies. The optimal policy, carbon tax, and fuel tax all raise retail fuel prices substantially, leading both to smaller cars and fewer miles traveled. The resulting reductions in other external damages are so large that these policies now have *negative* net carbon abatement costs of \$21/tCO2 or more. Meanwhile, since the size-based CAFE standard leads both to bigger cars and to more miles traveled, it dramatically increases other external damages. Thus, this policy becomes the single most costly policy at \$70.6/tCO2.

Alternative parameterizations

To test the sensitivity of our results to alternative assumptions, and to better understand what is driving our main results, we explore two alternative parameterizations of our model.

Consumer undervaluation of fuel economy

We next explore the role of consumer undervaluation in our model by setting the fuel economy valuation factor to $\beta = 0.75$. The baseline policies are now doing more to reduce carbon emissions, implying abatement of 5.3 billion tons (13%) below the no-policy baseline. In addition, this change implies, via the first-order conditions for fuel-economy improvements, that we now calibrate marginal costs to be lower than in the baseline calibration. At the same time, since consumers undervalue fuel economy improvements, inducing them to purchase marginally more efficient vehicles will incur *negative* surplus costs.

Table 7 presents simulation results based on this alternative calibration. When consumers undervalue fuel economy, the optimal policy, carbon tax, fuel tax, and CAFE standards all imply a negative average cost of carbon abatement, since inducing consumers to purchase more efficient cars through higher fuel prices and direct subsidies helps correct for this undervaluation. Indeed, the uniform CAFE standard now delivers private surplus gains that are bigger than either the carbon tax or fuel tax and nearly as big as the optimal policy. Since neither the LCFS nor the RFS induce consumers to invest substantially in higher fuel economy, however, the costs for these policies are little affected by consumer undervaluation.

Figure 3 presents second-best marginal abatement cost curves based on this alternative calibration. Cost curves for the baseline policy, optimal policy, taxes on carbon and fuel, and both fuel-economy standards are all shifted down relative to figure 2. In addition, observe that the cost curve for the optimal policy now closely follows the lower envelope of the cost curves for the uniform CAFE standard, the fuel tax, and finally the carbon tax. Why? Note that the optimal policy initially subsidizes fuel economy to correct for consumer undervaluation. Thus, the uniform CAFE standard performs nearly as well up to about 4 billion tons; the optimal policy performs slightly better, since it also subsidizes learning spillovers. After correcting for consumer undervaluation and learning spillovers, the optimal policy continues by taxing carbon. Thus, from about 4-10 billion tons, the carbon tax performs just as well. The fuel tax also performs just as well, since the carbon tax stimulates very little production of renewable fuels in this range. Beyond about 10 billion tons of abatement, however, the carbon tax begins to stimulate production of low-carbon fuels, thereby outperforming the fuel tax.

Both the traditional and size-based CAFE standards initially deliver abatement at lower marginal cost than either the carbon tax or fuel tax, as the standards more directly correct for consumer undervaluation. But their marginal costs rise quickly with additional abatement, as they fail to induce cost-effective reductions in miles traveled, and as the size-based standard fails to induce cost-effective reductions in car size.

Accounting for unpriced externalities has a qualitatively similar effect on relative abatement costs as when we assumed full valuation. In particular, taxes on carbon and fuel experience large reductions in net abatement costs, while the size-based fuel-economy standard experiences a large increase, and the uniform CAFE standard, LCFS, and quantity-based RFS are largely unaffected.

Learning-by-doing

We next explore the role of learning-by-doing in our model by setting the elasticity of the learning-by-doing knowledge-generation function to zero: $k = 0$. This change implies, via the first-order condition for cellulosic ethanol production in the first stage, that our calibration for marginal production costs in this stage is now lower than in the baseline calibration. At the same time, production in the first stage accrues no additional benefit in terms of lower production costs in the second stage, and deviations from baseline production in the first stage have no impact whatsoever on production costs in the second stage.

Table 8 presents simulation results based on this alternative calibration. As is clear from the table, the results are virtually identical to those in table 6, with the exception of the LCFS and RFS. The increase in first-stage cellulosic ethanol production under these policies generates no cost savings in the second stage. Thus, cellulosic ethanol production is lower under both the LCFS and RFS and there is a greater reliance on corn-based ethanol and sugarcane ethanol to generate abatement. Thus, the cost of meeting the carbon emissions target under both policies rises substantially—and the higher cost of low-carbon fuels under the LCFS drives up the overall price of fuel relative to the main calibration.

Figure 4 presents second-best marginal abatement cost curves based on this alternative calibration. Again, the results are qualitatively similar to the main calibration, with the exception of the LCFS and RFS. Whereas marginal costs for the LCFS and RFS under the main calibration were highly discontinuous, here they are mostly continuous, with only minor steps. Thus, it seems clear that the discontinuities we observe for the main calibration are related to cellulosic ethanol production turning on and off in one or both stages, leading to large jumps in the net marginal cost of production in one or both stages.

Conclusion

In this paper, we evaluate the impacts of multiple overlapping policies for reducing carbon emissions from light-duty vehicles and other externalities associated with the demand and supply of transportation fuels. To do this, we reformulate and extend the two-stage model of Fischer, Newell, and Preonas (2013) and apply it to the personal transportation sector. We find that the current mix of overlapping policies leads to substantial reductions in carbon emissions but induces behavioral changes that are highly cost-ineffective. Accordingly, we show that the optimal combination of policies can deliver the same level of carbon abatement but at substantially lower costs or even at a net welfare gain, depending on the degree of consumer undervaluation of fuel economy. Carbon taxes and fuel taxes consistently deliver carbon abatement at low or negative overall costs, especially when accounting for other unpriced externalities associated with vehicle size and miles traveled. Uniform fuel-economy standards can perform well when consumers undervalue fuel economy, but tend to have higher abatement costs under full valuation and after accounting for other unpriced externalities. Meanwhile, low-carbon fuel standards and renewable fuel standards consistently show higher abatement costs, as do size-based fuel-economy standards—whose costs increase dramatically after accounting for other unpriced externalities.

Our model and analysis could be extended in several fruitful ways. First, we could extend our analytical model to better distinguish between domestic and international producers and consumers of gasoline and ethanol, and then potentially connect the supply of gasoline and ethanol to global crude oil and agricultural markets. This would allow us to better differentiate between changes in domestic and international welfare and to measure changes in international carbon emissions (i.e., leakage). Second, we could use our current model or an extension to assess the distributional impacts of alternative policies (i.e., the winners and losers) across different sectors, different countries, and even different time periods. Finally, rather than calibrate the fuel supply curves based on EIA forecasts and modeling assumptions, we could dig deeper into making our own, independent assessment about the values of core parameters in our model and the future trajectory of demand and supply of transportation fuels. We leave these extensions to future work.

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Tables and Figures

Table 1 – Baseline Supply and Demand Parameters by Stage

	Stage 1	Stage 2
Slope of gasoline supply ($/BBTU per BBTU)	0.00086	0.00029
Slope of corn ethanol supply ($/BBTU per BBTU)	0.00471	0.00503
Slope of sugarcane ethanol supply ($/BBTU per BBTU)	0.02387	0.01665
Slope of cellulosic ethanol supply ($/BBTU per BBTU)	0.01022	0.00601
Slope of fuel economy supply via size (billion $/% per %)	0.33319	0.28564
Slope of fuel economy supply via technology (billion $/% per %)	0.05179	0.05501
Exogenous fuel demand growth rate (N_2/N_1-1)	–	0.1145
Stage length (years) (n_1 and n_2)	10	16
Discount factors on each stage (δ_1 and δ_2)	0.8108	0.4366

Table 2 – Other Baseline Parameters

	Base value
Emissions intensity of gasoline (tCO_2/BBTU) (μ_x)	101.14
Emissions intensity of corn ethanol (tCO_2/BBTU) (μ_m)	86.16
Emissions intensity of sugarcane ethanol (tCO_2/BBTU) (μ_b)	61.62
Emissions intensity of cellulosic ethanol (tCO_2/BBTU) (μ_w)	22.47
Learning parameter for cellulosic ethanol (k)	0.15
Degree of knowledge appropriability (ρ)	0.5
Short-run transportation demand elasticity (ε)	0.10
Ratio of discount factors between stages ($\delta = \delta_2/\delta_1$)	0.5385
Consumer fuel economy valuation factor (β)	1.00
Other external damages from miles ($/mile) ($dv$)	0.1077
Other external damages from miles x car size above reference size ($/mile-lb) ($dvs$)	0.000026664
Reference car size (lb) ($\bar{s}$)	1850

Table 3 – Baseline Results with Combination Policy (TAX + RFS-% + CAFE-SIZE)

	Stage 1	*Stage 2*
Retail price of transportation fuel (P_t) ($/BBTU)	25,923	29,617
Transportation fuel demand = supply (D_t) (BBTU)	15,041,000	12,596,000
Gasoline (q_t^x) (BBTU)	13,852,000	11,375,000
Corn ethanol (q_t^m) (BBTU)	1,103,000	11,198,000
Sugarcane ethanol (q_t^b) (BBTU)	71,539	81,145
Cellulosic ethanol (q_t^w) (BBTU)	14,303	19,545
Marginal cost of gasoline ($/BBTU)	21,636	25,849
Marginal cost of corn ethanol ($/BBTU)	32,675	31,997
Marginal cost of sugarcane ethanol ($/BBTU)	32,681	32,002
Marginal cost of cellulosic ethanol ($/BBTU)	43,428	36,156
Transportation fuel tax ($/BBTU)	3407	3166
RFS-Renewable target (ratio to gasoline)	0.0858	0.1073
RFS-Advanced target (ratio to gasoline)	0.0062	0.0089
RFS-Cellulosic target (ratio to gasoline)	0.0010	0.0017
Shadow value on RFS-Renewable ($/BBTU)	10159	5545
Shadow value on RFS-Advanced ($/BBTU)	5	5
Shadow value on RFS-Cellulosic ($/BBTU)	8179	4154
Miles traveled (billions)	2837	3216
Fuel consumption rate (BTU/mile)	5301	3917
Vehicle size (lbs)	3832	3617
Marginal cost of higher fuel economy via size (billion $/%)	3.8991	3.7305
Marginal cost of higher fuel economy via technology (billion $/%)	3.8891	4.1814
Size-based CAFE standard (BTU per mile-pound)	>1.3835	1.0828
Shadow value on higher fuel economy via technology (billion $/%)	0	0.4509
Total CO2 emissions (billion tCO_2)	1.5007	1.2524

Note: Shadow value on higher fuel economy via technology is scaled by size, such that units are in $ per % improvement in fuel economy, as in main text.

Table 4 – Marginal Abatement Cost ($/tCO2) for Different Abatement Strategies, Stage 1

PANEL A: SUBSTITUTE FUELS WHILE HOLDING OVERALL FUEL PRODUCTION FIXED

	INCREASE PRODUCTION		
DECREASE PRODUCTION	Corn	Sugarcane	Cellulosic
Gasoline	736.9	279.5	277.0
Corn		0.2	168.8
Sugarcane			274.6

PANEL B: DECREASE OVERALL FUEL PRODUCTION VIA CONSERVATION

	CONSERVATION METHOD		
DECREASE	Fewer miles	Smaller cars	Fuel-saving technology
Gasoline	42.4	42.4	42.4
Proportional decrease of all fuels	32.0	32.0	32.0

Table 5 – Marginal Abatement Cost ($/tCO2) for Different Abatement Strategies, Stage 2

PANEL A: SUBSTITUTE FUELS WHILE HOLDING OVERALL FUEL PRODUCTION FIXED

	INCREASE PRODUCTION		
DECREASE PRODUCTION	Corn	Sugarcane	Cellulosic
Gasoline	410.3	155.7	131.0
Corn		0.2	65.3
Sugarcane			106.1

PANEL B: DECREASE OVERALL FUEL PRODUCTION VIA CONSERVATION

	CONSERVATION METHOD		
DECREASE	Fewer miles	Smaller cars	Fuel-saving technology
Gasoline	37.3	37.3	72.7
Proportional decrease of all fuels	30.5	30.5	66.8

Table 6 – Comparison of Alternative Policies—Main Calibration

	(1) No Policy	(2) Baseline	(3) Optimal	(4) Carbon Tax	(5) Fuel Tax	(6) LCFS	(7) RFS	(8) CAFE-Trad	(9) CAFE-Size
Policy incentive in $/tCO2 (see note)	na	na	39.0	39.0	39.3	50.8	55.6	43.7	51.7
Fuel price 1 ($/billion BTU)	23343	25923	26472	26472	26499	23526	23158	22622	22605
Fuel price 2	26551	29618	33418	33418	33521	26626	25764	26111	26115
Fuel production 1 (billion BTU)	15833000	15041000	14885000	14885000	14878000	15773000	15894000	14997000	14977000
Gasoline	15833000	13852000	14885000	14885000	14878000	15534000	15618000	14997000	14977000
Corn ethanol	0	1103000	0	0	0	0	0	0	0
Sugarcane ethanol	0	71541	0	0	0	0	0	0	0
Cellulosic ethanol	0	14240	0	0	0	239540	276000	0	0
Fuel production 2 (billion BTU)	13851000	12596000	12378000	12378000	12358000	13833000	14050000	12284000	12297000
Gasoline	13814000	11379000	12216000	12216000	12358000	11230000	11079000	12284000	12297000
Corn ethanol	37397	1120000	161680	161680	0	170330	188160	0	0
Sugarcane ethanol	0	81202	0	0	0	0	0	0	0
Cellulosic ethanol	0	15768	0	0	0	2432600	2783400	0	0
Fuel use rate 1 (BTU/mile)	5548	5302	5253	5253	5250	5529	5566	5205	5197
Fuel use rate 2	4300	3917	3893	3893	3888	4295	4354	3756	3760
Car size 1 (lbs)	3855	3832	3827	3827	3827	3854	3857	3822	3891
Car size 2	3624	3617	3566	3566	3565	3623	3631	3545	3683
Fuel use-size ratio 1 (BTU per mile/lb)	1.439	1.384	1.373	1.373	1.372	1.435	1.443	1.362	1.335
Fuel use-size ratio 2	1.187	1.083	1.092	1.092	1.091	1.186	1.199	1.059	1.021
Energy cost of driving 1 ($/mile)	0.129	0.137	0.139	0.139	0.139	0.130	0.129	0.118	0.117
Energy cost of driving 2	0.114	0.116	0.130	0.130	0.130	0.114	0.112	0.098	0.098
Total driving 1 (billion miles)	2854	2837	2834	2834	2834	2853	2855	2881	2882
Total driving 2	3221	3216	3179	3179	3179	3221	3227	3271	3270
Cumulative emissions (billion tCO2)	38.42	35.05	35.05	35.05	35.05	35.05	35.05	35.05	35.05
Emissions 1	1.60	1.50	1.51	1.51	1.50	1.58	1.59	1.52	1.51
Emissions 2	1.40	1.25	1.25	1.25	1.25	1.21	1.20	1.24	1.24
Δ Discounted private surplus (billion $)	147.3	0.3	96.0	96.0	95.5	66.9	52.8	79.7	57.6
Δ Private surplus 1	11.0	0.0	9.2	9.2	9.2	5.9	5.1	9.1	8.4
Δ Private surplus 2	8.3	0.0	3.1	3.1	3.0	2.7	1.6	0.8	-1.5
Δ Discounted damages (billion $)	46.1	0.0	-77.1	-77.1	-78.5	42.3	59.4	66.9	194.4
Δ Damages 1	4.5	0.0	-0.9	-0.9	-0.9	4.2	4.8	6.4	11.8
Δ Damages 2	1.4	0.0	-10.0	-10.0	-10.2	1.2	2.9	2.2	14.2
Δ Discounted private surplus less damages (billion $)	101.2	0.3	173.1	173.1	174.0	24.5	-6.6	12.8	-136.8
Δ Private surplus less damages 1	6.5	0.0	10.1	10.1	10.1	1.7	0.2	2.7	-3.4
Δ Private surplus less damages 2	6.9	0.0	13.1	13.1	13.2	1.5	-1.2	-1.4	-15.7
Abatement cost, private surplus ($/tCO2)		43.7	15.2	15.2	15.4	23.8	28.0	20.0	26.6
Abatement cost, private surplus less damages ($/tCO2)		30.0	-21.3	-21.3	-21.6	22.7	32.0	26.2	70.6

Note: This table shows outcomes for alternative policies for the main calibration. Annual fuel prices and quantities, car attributes, and the energy cost and total amount of driving are shown separately for each stage (as indicated by the labels 1 and 2). Annual carbon emissions and welfare changes are shown separately for each stage (as indicated by the labels 1 and 2), along with cumulative undiscounted emissions and cumulative discounted welfare changes for 2015-2040. The no-policy scenario in column (1) turns off all policies, including state and federal fuel taxes. The baseline policy in column (2) includes state and federal fuel taxes, a percentage-based RFS, and size-based CAFE standards; table 3 presents the strength of each of these incentives. For the remaining policies, the first row of the table shows the stringency of each policy in equilibrium, scaled to have the same units ($/tCO2). The optimal policy in column (3) includes optimal cellulosic ethanol and fuel-economy subsidies (see the main text) and a carbon tax of $39.0/tCO2. The carbon tax in column (4) is also $39.0/tCO2. The fuel-tax in column (5) is $3979/BBTU, which scaled by the aggregate emissions rate gives $39.3/tCO2. The LCFS in column (6) has a shadow price of $50.8/tCO2. The RFS in column (7) subsidizes renewable fuels at a rate of $55.6/tCO2 avoided relative to gasoline. The traditional CAFE standard in column (8) would subsidize a 1% reduction in per-mile fuel consumption at $0.59 billion, which scaled by aggregate emissions yields $43.7/tCO2. Finally, the size-based CAFE standard in column (9) would subsidize a 1% reduction in per-mile fuel consumption at $0.70 billion, which scaled by aggregate emissions yields $51.7/tCO2. These carbon taxes, fuel taxes, LCFS shadow prices, RFS subsidy rates, and CAFE subsidy rates all correspond to stage 1 annual values and increase at the interest rate to stage 2—consistent with policies that regulate "cumulative" outcomes over stages 1-2 or, equivalently, that allow trading of compliance credits over time without penalty.

Table 7 – Comparison of Alternative Policies—Consumer Undervaluation of Fuel Economy

	(1) No Policy	(2) Baseline	(3) Optimal	(4) Carbon Tax	(5) Fuel Tax	(6) LCFS	(7) RFS	(8) CAFE-Trad	(9) CAFE-Size
Policy incentive in $/tCO2 (see note)	na	na	16.7	67.1	68.2	69.4	79.7	58.5	72.8
Fuel price 1 ($/billion BTU)	23282	25923	23489	28845	28934	23734	22973	22152	22118
Fuel price 2	26900	29618	29399	38753	39040	27388	25656	26209	26216
Fuel production 1 (billion BTU)	15762000	15041000	14043000	14338000	14318000	15632000	15853000	14451000	14412000
Gasoline	15762000	13852000	14043000	14338000	14318000	15260000	15404000	14451000	14412000
Corn ethanol	0	1103000	0	0	0	0	0	0	0
Sugarcane ethanol	0	71541	0	0	0	0	0	0	0
Cellulosic ethanol	0	14240	0	0	0	372190	448900	0	0
Fuel production 2 (billion BTU)	15133000	12596000	12891000	12755000	12709000	15012000	15455000	12625000	12650000
Gasoline	15026000	11379000	12818000	12401000	12709000	11010000	10703000	12625000	12650000
Corn ethanol	106770	1120000	72702	327830	0	260870	300200	0	0
Sugarcane ethanol	0	81203	0	25280	0	11304	51381	0	0
Cellulosic ethanol	0	15768	0	0	0	3729100	4400700	0	0
Fuel use rate 1 (BTU/mile)	5518	5302	4859	5087	5081	5480	5545	4983	4967
Fuel use rate 2	4751	3917	4015	4092	4079	4718	4838	3874	3882
Car size 1 (lbs)	3858	3832	3775	3805	3804	3854	3862	3791	3915
Car size 2	3574	3617	3453	3467	3465	3569	3587	3428	3670
Fuel use-size ratio 1 (BTU per mile/lb)	1.430	1.384	1.287	1.337	1.336	1.422	1.436	1.314	1.269
Fuel use-size ratio 2	1.329	1.083	1.163	1.180	1.177	1.322	1.349	1.130	1.058
Energy cost of driving 1 ($/mile)	0.128	0.137	0.114	0.147	0.147	0.130	0.127	0.110	0.110
Energy cost of driving 2	0.128	0.116	0.118	0.159	0.159	0.129	0.124	0.102	0.102
Total driving 1 (billion miles)	2856	2837	2890	2819	2818	2853	2859	2900	2901
Total driving 2	3185	3216	3210	3117	3116	3182	3194	3259	3258
Cumulative emissions (billion tCO2)	40.40	35.05	35.05	35.05	35.05	35.05	35.05	35.05	35.05
Emissions 1	1.59	1.50	1.42	1.45	1.45	1.55	1.57	1.46	1.46
Emissions 2	1.53	1.25	1.30	1.28	1.29	1.22	1.21	1.28	1.28
Δ Discounted private surplus (billion $)	83.6	0.3	154.9	128.1	129.8	-45.3	-113.8	146.7	91.6
Δ Private surplus 1	7.1	0.0	11.5	10.4	10.4	-0.5	-3.4	11.8	10.2
Δ Private surplus 2	3.7	0.0	8.9	6.3	6.5	-5.9	-12.3	7.3	1.3
Δ Discounted damages (billion $)	-17.7	0.0	-70.2	-235.0	-238.8	-31.9	5.4	-11.6	213.4
Δ Damages 1	5.1	0.0	4.2	-5.0	-5.2	4.2	5.7	7.0	16.7
Δ Damages 2	-8.4	0.0	-14.9	-27.8	-28.2	-9.4	-5.9	-9.7	11.1
Δ Discounted private surplus less damages (billion $)	101.3	0.3	225.1	363.1	368.7	-13.4	-119.2	158.2	-121.8
Δ Private surplus less damages 1	2.0	0.0	7.3	15.4	15.5	-4.7	-9.1	4.8	-6.5
Δ Private surplus less damages 2	12.2	0.0	23.7	34.1	34.8	3.5	-6.4	17.1	-9.9
Abatement cost, private surplus ($/tCO2)		15.6	-13.3	-8.3	-8.6	24.1	36.8	-11.8	-1.5
Abatement cost, private surplus less damages ($/tCO2)		18.9	-23.1	-48.9	-49.9	21.4	41.2	-10.6	41.6

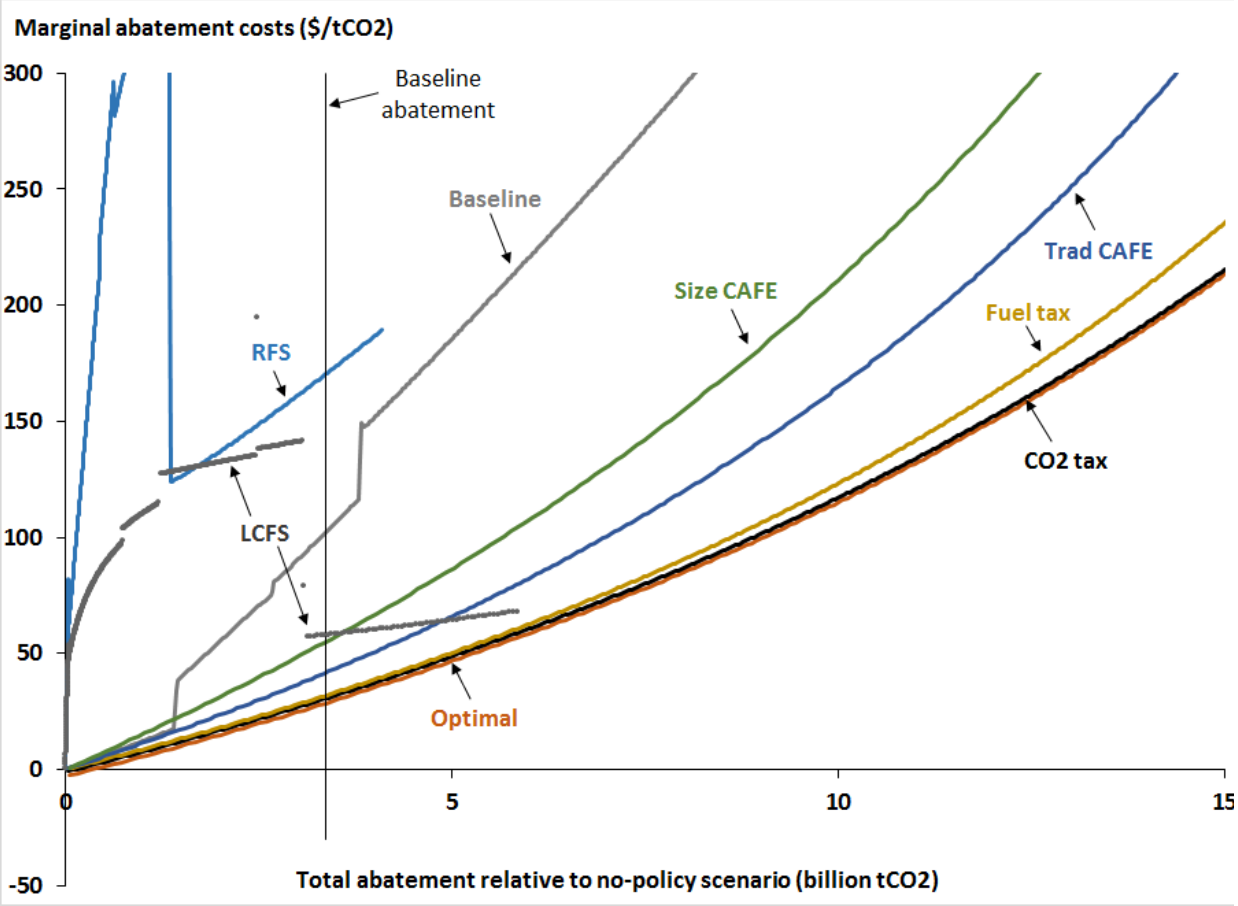
Note: This table shows outcomes for alternative policies, assuming that consumers only perceive 75% of the fuel savings associated with improved fuel economy. Annual fuel prices and quantities, car attributes, and the energy cost and total amount of driving are shown separately for each stage (as indicated by the labels 1 and 2). Annual carbon emissions and welfare changes are shown separately for each stage (as indicated by the labels 1 and 2), along with cumulative undiscounted emissions and cumulative discounted welfare changes for 2015-2040. The no-policy scenario in column (1) turns off all policies, including state and federal fuel taxes. The baseline policy in column (2) includes state and federal fuel taxes, a percentage-based RFS, and size-based CAFE standards. For the remaining policies, the first row of the table shows the stringency of each policy in equilibrium, scaled to have the same units ($/tCO2). The optimal policy in column (3) includes optimal cellulosic ethanol and fuel-economy subsidies (see the main text) and a carbon tax of $16.7/tCO2. The carbon tax in column (4) is $67.1/tCO2. The fuel-tax in column (5) is $6897/BBTU, which scaled by the aggregate emissions rate gives $68.2/tCO2. The LCFS in column (6) has a shadow price of $69.4/tCO2. The RFS in column (7) subsidizes renewable fuels at a rate of $79.7/tCO2 avoided relative to gasoline. The traditional CAFE standard in column (8) would subsidize a 1% reduction in per-mile fuel consumption at $0.79 billion, which scaled by aggregate emissions yields $58.5/tCO2. Finally, the size-based CAFE standard in column (9) would subsidize a 1% reduction in per-mile fuel consumption at $0.91 billion, which scaled by aggregate emissions yields $72.8/tCO2. These carbon taxes, fuel taxes, LCFS shadow prices, RFS subsidy rates, and CAFE subsidy rates all correspond to stage 1 annual values and increase at the interest rate to stage 2—consistent with policies that regulate "cumulative" outcomes over stages 1-2 or, equivalently, that allow trading of compliance credits over time without penalty.

Table 8 – Comparison of Alternative Policies—No Learning for Cellulosic Ethanol

	(1) No Policy	(2) Baseline	(3) Optimal	(4) Carbon Tax	(5) Fuel Tax	(6) LCFS	(7) RFS	(8) CAFE-Trad	(9) CAFE-Size
Policy incentive in $/tCO2 (see note)	na	na	39.0	39.0	39.3	146.6	180.3	43.7	51.7
Fuel price 1 ($/billion BTU)	23343	25923	26472	26472	26499	24171	23343	22622	22605
Fuel price 2	26551	29617	33418	33418	33521	27628	25505	26111	26115
Fuel production 1 (billion BTU)	15833000	15041000	14885000	14885000	14878000	15567000	15833000	14997000	14977000
Gasoline	15833000	13852000	14885000	14885000	14878000	15567000	15833000	14997000	14977000
Corn ethanol	0	1103000	0	0	0	0	0	0	0
Sugarcane ethanol	0	71539	0	0	0	0	0	0	0
Cellulosic ethanol	0	14303	0	0	0	0	0	0	0
Fuel production 2 (billion BTU)	13851000	12596000	12378000	12378000	12358000	13590000	14118000	12284000	12297000
Gasoline	13814000	11375000	12216000	12216000	12358000	10736000	10178000	12284000	12297000
Corn ethanol	37397	1119800	161680	161680	0	671760	826180	0	0
Sugarcane ethanol	0	81145	0	0	0	346670	485610	0	0
Cellulosic ethanol	0	19545	0	0	0	1835700	2627800	0	0
Fuel use rate 1 (BTU/mile)	5548	5302	5253	5253	5250	5465	5548	5205	5197
Fuel use rate 2	4300	3917	3893	3893	3888	4229	4373	3756	3760
Car size 1 (lbs)	3855	3832	3827	3827	3827	3848	3855	3822	3891
Car size 2	3624	3617	3566	3566	3565	3614	3634	3545	3683
Fuel use-size ratio 1 (BTU per mile/lb)	1.439	1.384	1.373	1.373	1.372	1.420	1.439	1.362	1.335
Fuel use-size ratio 2	1.187	1.083	1.092	1.092	1.091	1.170	1.203	1.059	1.021
Energy cost of driving 1 ($/mile)	0.129	0.137	0.139	0.139	0.139	0.132	0.129	0.118	0.117
Energy cost of driving 2	0.114	0.116	0.130	0.130	0.130	0.117	0.112	0.098	0.098
Total driving 1 (billion miles)	2854	2837	2834	2834	2834	2848	2854	2881	2882
Total driving 2	3221	3216	3179	3179	3179	3214	3229	3271	3270
Cumulative emissions (billion tCO2)	38.42	35.05	35.05	35.05	35.05	35.05	35.05	35.05	35.05
Emissions 1	1.60	1.50	1.51	1.51	1.50	1.57	1.60	1.52	1.51
Emissions 2	1.40	1.25	1.25	1.25	1.25	1.21	1.19	1.24	1.24
Δ Discounted private surplus (billion $)	147.0	0.0	95.7	95.7	95.2	-81.1	-225.0	79.4	57.3
Δ Private surplus 1	11.0	0.0	9.1	9.1	9.1	10.8	11.0	9.1	8.4
Δ Private surplus 2	8.3	0.0	3.1	3.1	3.0	-24.2	-44.9	0.8	-1.5
Δ Discounted damages (billion $)	46.1	0.0	-77.1	-77.1	-78.5	20.0	60.2	66.9	194.4
Δ Damages 1	4.5	0.0	-0.9	-0.9	-0.9	3.0	4.5	6.4	11.8
Δ Damages 2	1.4	0.0	-10.0	-10.0	-10.2	-0.6	3.4	2.2	14.2
Δ Discounted private surplus less damages (billion $)	100.9	0.0	172.8	172.8	173.7	-101.0	-285.2	12.5	-137.1
Δ Private surplus less damages 1	6.5	0.0	10.0	10.0	10.1	7.8	6.5	2.7	-3.4
Δ Private surplus less damages 2	6.9	0.0	13.1	13.1	13.2	-23.6	-48.3	-1.4	-15.7
Abatement cost, private surplus ($/tCO2)		43.6	15.2	15.2	15.4	67.6	110.3	20.0	26.6
Abatement cost, private surplus less damages ($/tCO2)		29.9	-21.3	-21.3	-21.6	59.9	114.5	26.2	70.6

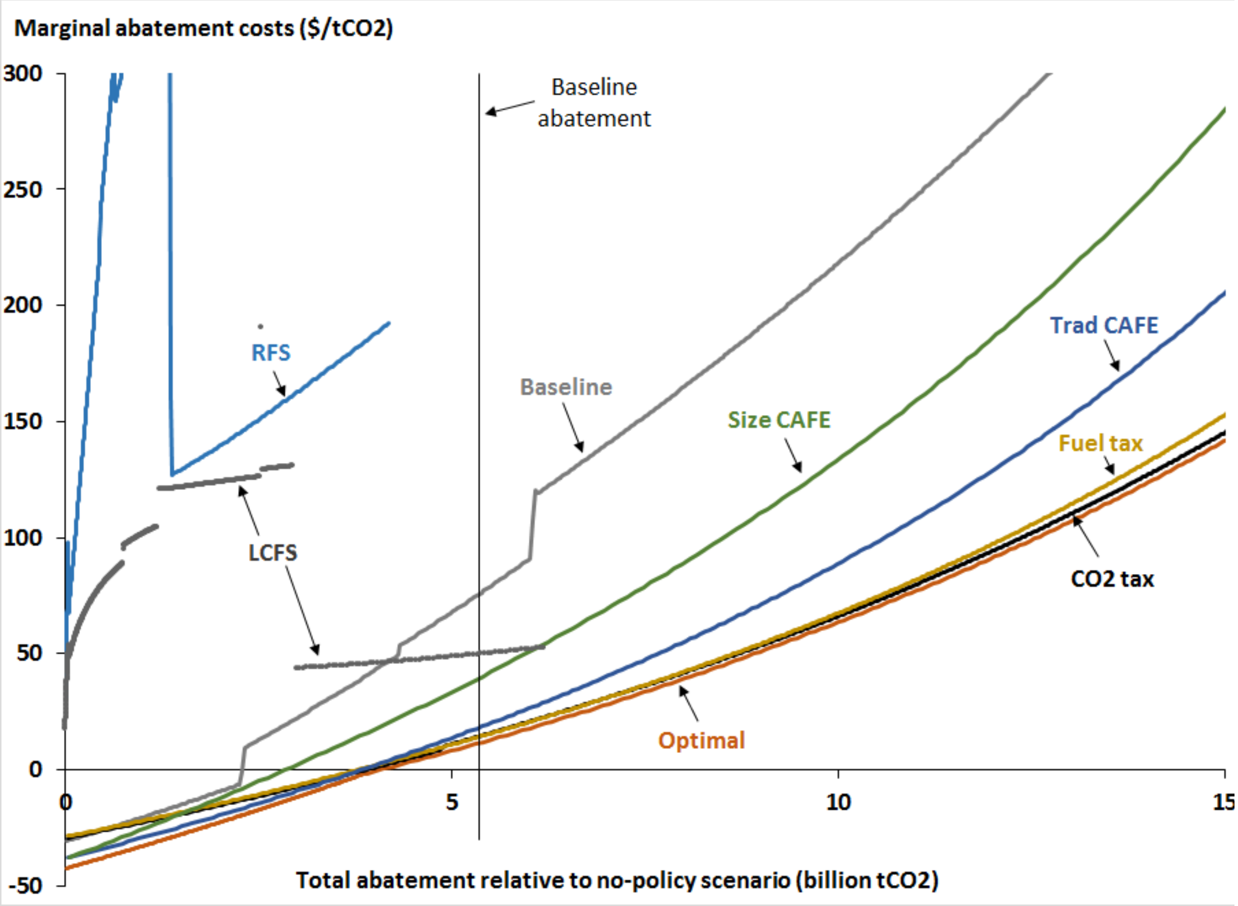
Note: This table shows outcomes for alternative policies, assuming that cellulosic ethanol production in stage 1 generates no learning-by-doing cost reduction in stage 2. Annual fuel prices and quantities, car attributes, and the energy cost and total amount of driving are shown separately for each stage (as indicated by the labels 1 and 2). Annual carbon emissions and welfare changes are shown separately for each stage (as indicated by the labels 1 and 2), along with cumulative undiscounted emissions and cumulative discounted welfare changes for 2015-2040. The no-policy scenario in column (1) turns off all policies, including state and federal fuel taxes. The baseline policy in column (2) includes state and federal fuel taxes, a percentage-based RFS, and size-based CAFE standards. For the remaining policies, the first row of the table shows the stringency of each policy in equilibrium, scaled to have the same units ($/tCO2). The optimal policy in column (3) includes optimal cellulosic ethanol and fuel-economy subsidies (see the main text) and a carbon tax of $39.0/tCO2. The carbon tax in column (4) is also $39.0/tCO2. The fuel-tax in column (5) is $3979/BBTU, which scaled by the aggregate emissions rate gives $39.3/tCO2. The LCFS in column (6) has a shadow price of $146.6/tCO2. The RFS in column (7) subsidizes renewable fuels at a rate of $180.3/tCO2 avoided relative to gasoline. The traditional CAFE standard in column (8) would subsidize a 1% reduction in per-mile fuel consumption at $0.59 billion, which scaled by aggregate emissions yields $43.7/tCO2. Finally, the size-based CAFE standard in column (9) would subsidize a 1% reduction in per-mile fuel consumption at $0.70 billion, which scaled by aggregate emissions yields $51.7/tCO2. These carbon taxes, fuel taxes, LCFS shadow prices, RFS subsidy rates, and CAFE subsidy rates all correspond to stage 1 annual values and increase at the interest rate to stage 2—consistent with policies that regulate "cumulative" outcomes over stages 1-2 or, equivalently, that allow trading of compliance credits over time without penalty.

Figure 2 – Second-Best Marginal Abatement Costs—Main Calibration



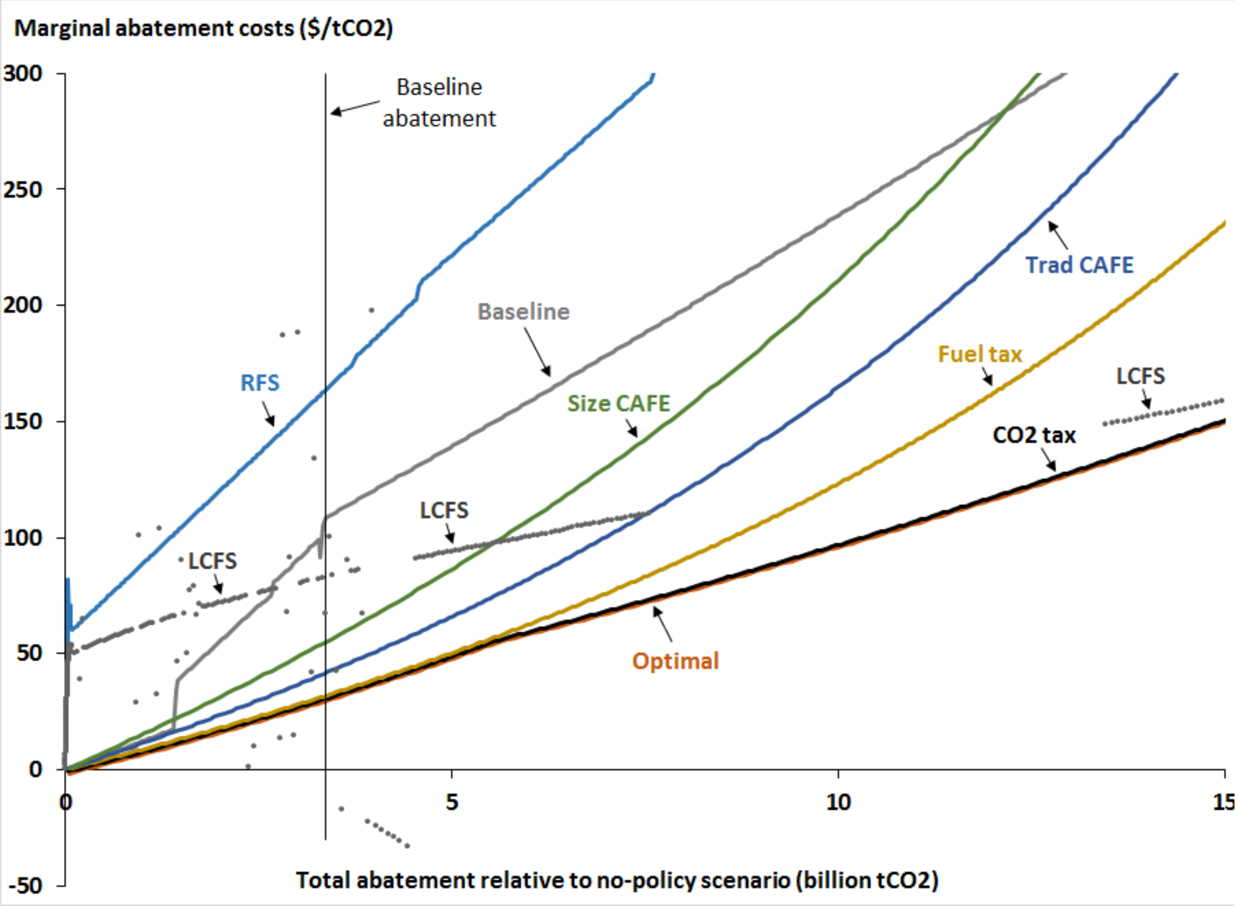
Note: To calculate the second-best marginal abatement cost curve for a given policy, we start from the no-policy baseline and gradually ramp up the corresponding policy's incentives, calculating the change in private welfare cost per change in carbon emissions at each iteration. For the baseline policy, we gradually and simultaneously increase state and federal fuel taxes, the shadow price on the size-based CAFE standard, and the shadow prices on the RFS constraints, starting from zero, in proportion to their values under the baseline policy. For the optimal policy, we first gradually and simultaneously phase-in the optimal subsidies to cellulosic ethanol, and then, once these optimal subsidies are fully phased-in, we continue by gradually increasing the carbon tax. For the LCFS, we gradually increase the assumed shadow price on the LCFS constraint, solving for the corresponding equilibrium carbon emissions rate at each iteration. We consider a quantity-based RFS that implicitly subsidizes renewable fuels in proportion to their carbon emissions relative to gasoline, as described in the main text; we trace out the marginal abatement cost curve by gradually increasing the proportional subsidy rate. For the uniform CAFE standard, we gradually increase the subsidy to percent fuel economy improvements, and likewise for the size-based CAFE standard, but limiting the subsidy to improvements via technology. As described in the text, we assume that carbon taxes, the fuel tax, the LCFS shadow price, implicit subsidies under the RFS, and CAFE-related subsidies all increase at the between-period discount rate from stage 1 to stage 2.

Figure 3 – Second-Best Marginal Abatement Costs—Undervaluation of Fuel Economy



Note: To calculate the second-best marginal abatement cost curve for a given policy, we start from the no-policy baseline and gradually ramp up the corresponding policy's incentives, calculating the change in private welfare cost per change in carbon emissions at each iteration. For the baseline policy, we gradually and simultaneously increase state and federal fuel taxes, the shadow price on the size-based CAFE standard, and the shadow prices on the RFS constraints, starting from zero, in proportion to their values under the baseline policy. For the optimal policy, we first gradually and simultaneously phase-in the optimal subsidies to fuel economy and cellulosic ethanol, and then, once these optimal subsidies are fully phased-in, we continue by gradually increasing the carbon tax. For the LCFS, we gradually increase the assumed shadow price on the LCFS constraint, solving for the corresponding equilibrium carbon emissions rate at each iteration. We consider a quantity-based RFS that implicitly subsidizes renewable fuels in proportion to their carbon emissions relative to gasoline, as described in the main text; we trace out the marginal abatement cost curve by gradually increasing the proportional subsidy rate. For the uniform CAFE standard, we gradually increase the subsidy to percent fuel economy improvements, and likewise for the size-based CAFE standard, but limiting the subsidy to improvements via technology. As described in the text, we assume that carbon taxes, the fuel tax, the LCFS shadow price, implicit subsidies under the RFS, and CAFE-related subsidies all increase at the between-period discount rate from stage 1 to stage 2.

Figure 4 – Second-Best Marginal Abatement Costs—No Learning for Cellulosic Ethanol



Note: To calculate the second-best marginal abatement cost curve for a given policy, we start from the no-policy baseline and gradually ramp up the corresponding policy's incentives, calculating the change in private welfare cost per change in carbon emissions at each iteration. For the baseline policy, we gradually and simultaneously increase state and federal fuel taxes, the shadow price on the size-based CAFE standard, and the shadow prices on the RFS constraints, starting from zero, in proportion to their values under the baseline policy. For the optimal policy, we gradually increase the carbon tax (there is no learning, so optimal cellulosic ethanol subsidies are zero). For the LCFS, we gradually increase the assumed shadow price on the LCFS constraint, solving for the corresponding equilibrium carbon emissions rate at each iteration. We consider a quantity-based RFS that implicitly subsidizes renewable fuels in proportion to their carbon emissions relative to gasoline, as described in the main text; we trace out the marginal abatement cost curve by gradually increasing the proportional subsidy rate. For the uniform CAFE standard, we gradually increase the subsidy to percent fuel economy improvements, and likewise for the size-based CAFE standard, but limiting the subsidy to improvements via technology. As described in the text, we assume that carbon taxes, the fuel tax, the LCFS shadow price, implicit subsidies under the RFS, and CAFE-related subsidies all increase at the between-period discount rate from stage 1 to stage 2.

Appendix

Model equations

Fossil fuels

Let $C_t^x(q_t^x)$ denote the total cost of producing quantity q_t^x of gasoline in period t, with the properties $C_t'^x(q_t^x) > 0$ and $C_t''^x(q_t^x) \geq 0$, where the single and double prime denote first and second partial derivatives. Here and elsewhere, lettered superscripts index different fuel types, while numbered time-*t* subscripts index different time periods. Profits for conventional fuel suppliers are revenues less production costs and net taxes paid:

$$\pi^x = \delta_1 n_1 \left((P_1 - \phi_1^x) q_1^x - C_1^x(q_1^x) \right) + \delta_2 n_2 \left((P_2 - \phi_2^x) q_2^x - C_2^x(q_2^x) \right). \tag{A.13}$$

Maximizing these profits with respect to output in each period yields (1). If marginal costs at zero exceed the fuel price less then net tax, however, then production is optimally set to zero.

Mature biofuels

We have upward-sloping supply curves for corn-based and imported ethanol: $C_t'^i(q_t^i) > 0$ and $C_t''^i(q_t^i) > 0$ for *i* = {*m*,*s*}. In our two-stage model, profits for the representative producer of mature renewable fuel type *j* = {*m*,*b*} are given by

$$\pi^j = \delta_1 n_1 \left(\left(P_1 - \phi_1^j \right) q_1^j - C_1^j(q_1^j) \right) + \delta_2 n_2 \left(\left(P_2 - \phi_2^j \right) q_2^j - C_2^j(q_2^j) \right), \tag{A.14}$$

where prices, quantities, and costs have the same interpretation as for gasoline above. Thus, maximizing profits with respect to output in each period yields (2). However, if marginal costs at zero exceed the fuel price less then net tax, then production is optimally set to zero.

Cellulosic ethanol

Cellulosic ethanol production costs are given by $G_t^w(K_t^w, q_t^w)$, which is increasing and convex in production q_t^w and declining and convex in the knowledge stock K_t^w, so that $G_q > 0$, $G_{qq} > 0$, $G_K < 0$, and $G_{KK} > 0$, where the lettered subscripts here denote partial derivatives with respect to production and/or knowledge, and we have suppressed the time and fuel-type subscripts to avoid clutter. Note that since marginal costs are declining in knowledge and the cross-partial derivatives are symmetric, we also have $G_{qK} = G_{kQ}$. The knowledge stock $K^w(Q_t^w)$ is an increasing function of cumulative experience through LBD, given by Q_t^w. That is, $K_Q \geq 0$, where we have again suppressed subscripts and superscripts to avoid clutter. Annual production is still q_t^w, as indicated above. Thus, cumulative experience in the second period is given by $Q_2 = Q_1 + n_1 q_1$.

Profits for the representative producer of cellulosic ethanol are then given by

$$\pi^w = \delta_1 n_1 \left((P_1 - \phi_1^w) q_1^w - G_1^w(K_1^w, q_1^w) \right) + \delta_2 n_2 \left((P_2 - \phi_1^w) q_2^w - G_2^w(K_2^w, q_2^w) \right) \tag{A.15}$$

where $K_2^w = K^w(Q_2^w)$.

Recall that the appropriation factor ρ does not enter directly into the aggregate profit function, which reflects operating profits, but it does enter into the first-order conditions for learning in the first stage, as given by (4).

Consumer demand

Aggregate net consumer utility as a function of VMT and the rates of each type of fuel-economy improvement in each stage is given by:

$$\begin{aligned} U = {} & \delta_1 n_1 \left(u(v_1) - P_1 v_1 \psi_1^0 e^{-\theta_1} - Z_1^s(\theta_1^s) - Z_1^r(\theta_1^r) + \sigma_1^s \theta_1^s + \sigma_1^r \theta_1^r \right) \\ & + \delta_2 n_2 \left(u(v_2) - P_2 v_2 \psi_2^0 e^{-\theta_2} - Z_2^s(\theta_2^s) - Z_2^r(\theta_2^r) + \sigma_2^s \theta_2^s + \sigma_2^r \theta_2^r \right), \end{aligned} \tag{A.16}$$

where σ_t^s and σ_t^r are the subsidies for percent improvements in fuel economy via reductions in size and improvements in technology in period $t = \{1,2\}$.

In period t, given any energy consumption rate per unit of service (which is determined simultaneously), the representative consumer uses energy services until the marginal utility equals the marginal fuel costs of those services:

$$u_t'(v_t) = P_t \psi_t \tag{A.17}$$

Let $D_t(P_t, \psi_t)$ be the derived consumer demand for transportation energy, which is a function of the price and an energy consumption rate. Because $D = \psi v$, we can rewrite the energy demand function as $D_t = \psi_t u'^{-1}\left(P_t \psi_t\right)$. To derive fuel demand, we assume that the utility consumers derive from VMT is $u(v_t) = -\mathrm{A}_t v_t^{-\alpha}$, where A is a scalar that also allows for exogenous demand growth and $\alpha > 0$. In period *t*, the quantity of fuel demanded is $D_t = \psi_t v_t$, and we can equivalently write the consumer first-order condition for VMT as

$$\alpha \mathrm{A}_t \left(\frac{D_t}{\psi_t} \right)^{-\alpha} / D_t = P_t$$

Note that the CAFE constraint does not enter into the VMT choice.

We can rewrite this expression in terms of the price elasticity of demand:

$$D_t = \psi_t^{\frac{\alpha}{1+\alpha}} \left(\frac{P_t}{\alpha \mathrm{A}_t} \right)^{\frac{-1}{1+\alpha}} = N_t \psi_t^{1-\varepsilon} P_t^{-\varepsilon} \tag{A.18}$$

where $\alpha = (1-\varepsilon)/\varepsilon$ and $N_t = \mathrm{A}_t^{\varepsilon} (\varepsilon / (1-\varepsilon))^{-\varepsilon}$, and $0 < \varepsilon < 1$. The elasticity ε can be interpreted as a very short run elasticity, as might be reflected in the rebound effect.

Revenues

We denote changes in government revenues by *V*, which equals total tax revenues less subsidies:

$$V = \delta_1 n_1 \left(\sum_{i=x,m,b,w} \phi_1^i q_1^i - \sigma_1^s \theta_1^s - \sigma_1^r \theta_1^r \right) + \delta_2 n_2 \left(\sum_{i=x,m,b,w} \phi_2^i q_2^i - \sigma_2^s \theta_2^s - \sigma_2^r \theta_2^r \right). \tag{A.19}$$

Economic surplus

In our partial equilibrium model, we define the change in *economic surplus* relative to baseline simply as the sum of the changes in consumer and producer surplus, the change in direct revenue transfers from taxes and subsidies, and the change in total other external damages due to changes in vehicle size and miles traveled. Thus,

$$\Delta W = \Delta U + \sum_i \pi^i + \Delta V + \Delta OD. \tag{A.20}$$

Since consumer payments to firms and tax and subsidy payments are transfers, we can simplify the representation of economic surplus to be

$$\begin{aligned} W = {} & \delta_1 n_1 \left(u(v_1) - Z_1^s(\theta_1^s) - Z_1^r(\theta_1^r) - \sum_{i=x,m,s} C_1^i(q_1^i) - G^w(K_1^w, q_1^w) - OD_1 \right) \\ & + \delta_2 n_2 \left(u(v_2) - Z_2^s(\theta_2^s) - Z_2^r(\theta_2^r) - \sum_{i=x,m,s} C_2^i(q_2^i) - G^w(K_2^w, q_2^w) - OD_2 \right) \end{aligned} \tag{A.21}$$

Our model focuses on the private welfare implications associated with policies to reduce carbon emissions in the United States. Welfare changes associated with consumer utility and other external damages accrue 100% domestically. However, welfare and emissions changes associated with fuel supply may partly accrue elsewhere. In particular, gasoline supply in our calibration reflects the residual supply of gasoline to the United States, after subtracting rest-of-the-world demand from global supply. In addition, the physical supply of Brazilian sugarcane ethanol rests entirely outside of the United States and reflects net imports to the United States after subtracting off rest-of-the-world demand for Brazil's ethanol. Even corn-based ethanol and cellulosic ethanol supply may partly reflect welfare changes elsewhere via international trade in food and other agricultural commodities.

Thus, an interesting future extension to our model would be to recognize the global nature of transportation fuel and agricultural markets and distinguish between global and domestic welfare, accounting for imports and exports, terms-of-trade effects, and changes in foreign surplus and emissions. However, for now we wish to focus on policy interactions and innovation. Thus, we only consider U.S. emissions, and we do not trace policy impacts up the various fuels' supply chains, as these issues are better studied with a global trade model.[35] In practice, our model will largely reflect changes in domestic U.S. welfare, given that the gasoline supply curve we calibrate is quite flat, given that the supply chains for corn-based and cellulosic ethanol are largely domestic, and given that the total quantity of ethanol supplied is relatively low.

Functional forms in the numerical model

For conventional (non-innovating) fuels, the costs all take the following form: $C_{it}(q_t^i) = c_{0t}^i + c_{1t}^i \cdot (q_t^i - q_{0t}^i) + c_{2t}^i \cdot (q_t^i - q_{0t}^i)^2 / 2$, where q_{0t}^i is the baseline output in stage *t* for source *i*. Furthermore, from the first-order conditions for the baseline, the incremental marginal cost is $c_{1t}^i = P_t - \phi_t^i$, where the P_t and ϕ_t^i here are the fuel price and net tax on fuel type *i* in the baseline. We assume that total baseline cost, c_{0t}^i, is equal to the total area under the variable cost curve in the baseline. This assumption has no effect on the results and is therefore totally innocuous.

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[35] For example, if U.S. policies affect global oil prices, foreign welfare and emissions will respond. Such effects have been the subject of a long literature on carbon leakage using computable general equilibrium models. See, e.g., Böhringer et al. 2012.

For advanced biofuels, the cost function is inversely related to the knowledge stock: $G_t\left(K_t^a, q_t^a\right) = \left(g_{0t} + g_{1t}\cdot(q_t^a - q_{0t}^a) + g_{2t}\cdot(q_t^a - q_{0t}^a)^2 / 2\right)\left(K_{0t}^a / K_t^a\right)$, so that technological change lowers both the intercept and the slope of the renewable fuel's supply curve. Furthermore, as above, we assume that total baseline cost, g_{0t}^i, is equal to the area under the variable cost curve in the baseline. As in Fischer, Newell, and Preonas (2013), we assume that the relationship between the knowledge stock and cumulative experience takes a constant elasticity form, as is common in this literature: $K_2\left(Q_2\right) = \left(Q_2 / Q_1\right)^k$, implying that $K_1 = 1$. From the first-order conditions, and with these functional forms, the baseline marginal cost is therefore $g_{11} = P_1 - \phi_1^w + k\delta\rho n_2 g_{02} / Q_{02}^w$ and $g_{12} = P_2 - \phi_2^w$, where again the P_t and ϕ_t^w here are the fuel price and net tax on fuel type *i* in the baseline.

As described in (5), we assume a utility function that leads to constant elasticity demand for fuel: $D_t = N_t \psi_t^{1-\varepsilon} P_t^{-\varepsilon}$, where $0 < \varepsilon < 1$. We assume a linear marginal cost for percent changes in fuel economy around the baseline, such that for each type of improvement *j*={*s*,*r*}, costs are a quadratic function: $Z_t^j(\theta_t^j) = z_{1t}^j \theta_t^j + z_{2t}^j \cdot (\theta_t^j)^2 / 2$, with marginal costs given by $Z_t^{j\prime}(\theta_t^j) = z_{1t}^j + z_{2t}^j \theta_t^j$ and slope given by $Z_t^{j\prime\prime}(\theta_t^j) = z_{2t}^j$. We normalize $\theta_t^j = 0$ in the baseline, such that from the first-order conditions (6) and (7) we have $z_{1t}^s = \beta P_t D_t + 0$ and $z_{1t}^r = \beta P_t D_t + \sigma_t^{r,CAFE-SIZE}$, where P_t and D_t here are the fuel price and total fuel consumption in the baseline. In other words, the intercept of the marginal cost function is determined in part by our assumptions regarding the perceived valuation factor for each type of fuel-economy improvement, and the stringency of the size-based CAFE constraint in the baseline.