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Abstract

Fuel economy standards are the workhorse of U.S. policy to reduce emissions and oil use by the light duty fleet, and are slated to be dramatically tightened over the next decade. This paper elucidates the relationship between fuel economy standards and "feebate" policies that penalize low fuel economy vehicles with a fee and reward high fuel economy vehicles with a rebate. The analytical results show how a feebate can be designed to exactly match a fuel economy standard, both under the previous regulation and the current regulation. Moreover, I prove how the current footprint-based standard leads to a perverse incentive to upsize vehicles, and how this could carry over to a "footprint-based feebate." To more concretely show the effects of both policies, I use the National Energy Modeling System modified for this study (NEMS-NEPI) to simulate the current fuel economy standards and an equivalently stringent feebate policy. Both policies are found to have broadly similar effects, although the implementation of these policies in NEMS-NEPI leads to minor differences in the uptake of different vehicle technologies. This paper highlights the importance of the policy details in the final welfare implications of both fuel economy standards and feebates. For reasons of policy transparency, complementary policies, and administrative costs, one could make a reasonable case for preferring feebates over fuel economy standards, but the final verdict depends on the particular standard and feebate policy implemented.

Executive Summary

When it comes to policies to reduce oil use and emissions from the light duty fleet, fuel economy standards have been the most prominent – and perhaps most debated – policy at the national level. Corporate Average Fuel Economy (CAFE) standards are often critiqued as an economically inefficient regulatory approach. While economists most commonly point to an increased gasoline tax as the preferred alternative, such an increase if often considered politically infeasible. Another proposed alternative policy is a “feebate” that penalizes low fuel economy vehicles with a fee and rewards high fuel economy vehicles with a rebate. Such a feebate policy is sometimes described as a more market-based policy than the traditional CAFE standards policy in the sense that it increases the fuel economy of the fleet simply by changing the relative prices of new vehicles.

This paper lays out the economics of feebate policies in relation to both the previous CAFE standards before model year 2011 and the revised CAFE standards that started with model year 2011. Before model year 2011, CAFE standards required each automaker to meet or exceed a sales-weighted harmonic average fuel economy target for both the passenger vehicle and light truck fleet, where sport utility vehicles are classified as light trucks. Each fleet was treated separately and there was no trading of CAFE credits either between fleets or across automakers. This changed dramatically with model year 2011. Starting with model year 2011, the CAFE regulation allowed trading of CAFE credits across an automaker’s vehicle lineup and even across manufacturers. At the same time, a separate CAFE standard is assigned to each vehicle “footprint” (wheelbase times length) based on the fleet. These changes to the CAFE standard are critical factors in the welfare implications of the policy.

This paper makes an important contribution by analytically clarifying the incentives provided by feebates and different CAFE standard policies, leading to several insights. First, for any binding CAFE standard policy, an equivalent feebate policy can be found via a simple relationship between the parameters governing the two policies. Moreover, the relationship between the two policies holds regardless of whether the CAFE policy has a single fleet, two fleets, or is footprint-based. If there is a CAFE standard with multiple fleets, the equivalent feebate will have multiple fleets, each with a separate “pivot point” that determines the switch from a fee to a rebate.

More importantly, an equivalence also holds regardless of whether there is trading of CAFE permits in the CAFE standard policy. However, CAFE standards are clearly more cost-effective when CAFE credit trading is permitted. Similarly, a feebate designed to match a CAFE standard where credit trading is permitted would be more cost-effective than one that is not. However, the gain in cost-effectiveness from trading may be countered when either policy instrument is simultaneously is moved to a footprint-based policy. A footprint-based policy will lead automakers to increase the footprint of vehicles, with an associated loss in economic efficiency due to greater accident risk. A footprint-based policy may be preferred for mitigating the effects of CAFE credit trading on U.S. automakers, but the loss in economic efficiency must be weighed against this political motivation carefully.

After clarifying the theoretical relationship between CAFE standard policies and feebates, this paper uses the National Energy Modeling System modified for this study (NEMS-NEPI) to perform a numerical simulation of both the current CAFE standards policy through 2025 and a feebate policy designed to meet nearly the same fuel economy targets each year through 2025. The modeled policies lead to an increase in 2025 fuel economy to 48 miles per gallon and 47 miles per gallon respectively. The increase is significant relative to the reference case with a fuel economy of 37 miles per gallon. This increase in fuel economy is associated with a considerable decrease in 2025 motor gasoline use: from 19.3 million barrels/day of oil use to 18.8 million barrels/day. Oil imports in 2025 drop from 7.1 million barrels/day to 6.6 million barrels/day. U.S. GDP does not change appreciably and total vehicle miles driven by the entire light duty fleet of vehicles increases slightly due to the rebound effect. The CAFE standard and feebate policy differ in the number of conventional hybrids, microhybrids, and dedicated electric vehicles produced, as well as the rebound effect, although these differences are largely due to the structure of NEMS-NEPI, which limits how exactly each of the policies is implemented. These differences translate into a difference in estimates of social welfare. Looking at CAFE standards, under central-case assumptions, the 2025 welfare cost of reducing greenhouse gases – assuming undervaluation of future fuel savings – is \$154/ton CO_2-e (in 2010\$). The 2010-2035 present discounted value policy costs are \$195 billion with a 5% social discount rate. Of course, these estimates do not account for benefits from reducing national security or local criteria air pollution externalities.

The findings of the paper indicate that a feebate policy may be very similar to CAFE standard and that the details of the policy implementation, such as whether CAFE credits are tradable and whether a footprint-based policy is used, are key determinants of the cost-effectiveness. The paper also highlights where CAFE standards and feebates differ. If CAFE standards do not allow for tradable CAFE credits, then standards may not be binding on some automakers. In contrast, a feebate would provide continual incentives for improving fuel economy. Feebates will also perform much better when there are complementary policies, such as state-level subsidy policies. CAFE standards would render these state-level policies ineffective at reducing net emissions or oil use. Feebates and CAFE standards may also differ in administrative costs. One might expect feebates to have lower administrative costs, although this would depend on the details of the feebate implemented. Finally, the simplicity and transparency of a feebate may be a major advantage. There are many loopholes and details in the current CAFE standards that were implemented for political expediency and may reduce the cost-effectiveness of the policy. With a transparent feebate, these policy features may be less likely. These differences may just tip the scale in favor of a feebate policy over CAFE standards.

1. Introduction

Transportation energy use accounts for over one third of all carbon dioxide emissions in the United States, with over 60 percent of these emissions from the combustion of motor gasoline and diesel fuel (EIA 2009a). Passenger vehicle transportation continues to rely almost entirely on motor gasoline and diesel fuel, with these fuels making up over 65 percent of all transportation liquid fuels consumed (EIA 2011). Moreover, passenger vehicle energy use has been on an upward trend over the past 30 years, albeit with slight declines during periods with higher fuel prices (Davis et al. 2009).

Accordingly, there has been intense policy interest in reducing energy use from passenger vehicles. Economists have long pointed to environmental and energy security externalities to motivate policy to reduce the use of oil in transportation. There are many policy instruments that have the potential to reduce emissions and our reliance on oil. Fuel economy standards, fuel taxes, fees per mile driven, pricing on congested roadways, incentives for new alternative fuel vehicles, and subsidies or fees on new vehicles based on fuel economy are all plausible alternatives, and indeed, all of these instruments have been implemented to varying degrees throughout the world. Much of policy activity in the United States over the past several decades has focused on improving new vehicle fuel economy through Corporate Average Fuel Economy (CAFE) standards. In the latest proposed rulemaking, the Obama administration plans to continue to tighten CAFE standards such that by 2025, most new vehicles will match the 2012 Toyota Prius (3rd Gen Prius) fuel economy (NHTSA 2012).

Some analysts have suggested that rather than CAFE standards, we would be better off with a "feebate" policy that levies a fee on low fuel economy vehicles and provides a rebate for high fuel economy vehicles. Such a policy has been implemented in Canada, France, and Denmark, and has been widely discussed as an option for California, Maryland, and the entire United States (Langer 2005; Bunch et al. 2012; D'Haultfoeuille et al. 2012). Both CAFE standards and feebates have the very practical advantage that they are more likely to be politically feasible than many other policies, such as increased fuel taxes or a tax on carbon dioxide emissions. Of course, since both do not disincentize many emitting activities, such as driving, economists have long considered them suboptimal policies from an economic efficiency standpoint (Fischer 2009). However, whether there are greater net social benefits from CAFE standards or feebates is an important question for practical policy-making given the very real political feasibility constraints.

This paper develops a theoretical framework to compare CAFE standards to feebates and then performs a numerical simulation to illustrate the differences between the two policies. The theoretical framework clarifies the considerable similarities between CAFE standards and feebates, demonstrating how to design a feebate that provides identical incentives to automobile manufacturers as CAFE standards. This equivalence is shown to hold both with and without trading of CAFE permits. When CAFE standards are based on the footprint of the vehicle, as in the currently enacted CAFE standards, obtaining this equivalence may not be feasible. Moreover, footprint-based CAFE standards, CAFE standards will multiple fleets, and a feebate with multiple fleets all provide an incentive for manufacturers to alter the attributes of the vehicle in order to qualify the vehicle for a different standard or different feebate structure. These results are new to the literature and illuminate exactly how and when CAFE standards and feebates are equivalent.

To more concretely illustrate the similarities and differences between CAFE standards and feebates, I use the Energy Information Administration (EIA) National Energy Modeling System (NEMS) with some minor modifications for this study (NEMS-NEPI) to simulate the recently enacted CAFE standards and a revenue-neutral feebate policy designed to closely match the fuel economy of the CAFE standard. NEMS is well-documented and widely used for policy analyses and projections, including the *Annual Energy Outlook (AEO) 2012* (EIA 2012). Unlike many previous modeling efforts examining feebates (e.g., Train et al. (1997) and Bunch et al. (2012)) this study aims to match a feebate as closely as possible to the proposed CAFE standards to explore the effects of a switch from the currently enacted regulation to a similar feebate policy.[1]

While NEMS-NEPI has some limitations, its comprehensiveness and detail in modeling the light duty fleet make it a useful modeling tool. The results from the NEMS-NEPI simulations indicate that a revenue-neutral feebate can be constructed to very closely match the current CAFE standards in terms of fleet-wide new vehicle fuel economy. The results highlight just how similar the feebate could come to a given CAFE standard in terms of a variety of other indicators as well. Both the currently proposed CAFE standards and the modeled feebate policy can increase light duty fuel economy by 30 percent by 2025, reducing gasoline consumption by nearly eight percent and oil imports by six percent. The policy costs vary widely depending on the assumptions made, but under a reasonable set of assumptions, the 2025 welfare cost of reducing greenhouse gases – assuming undervaluation of future fuel savings – is \$154/ton CO_2-equivalent (in 2010\$). The 2010-2035 present discounted value policy costs amount to \$195 billion with a 5% social discount rate.

The paper is organized as follows. The next section provides background on the institutional details of CAFE standards in the United States and several of the implemented feebate policies around the world. Section 3 presents the analytical framework to clarify the differences between CAFE standards and feebates. Section 4 provides an overview of the NEMS-NEPI model and then details the results from numerical simulations using the model. Finally, Section 5 concludes.

[1] Small (2010) performs a similar analysis using a slightly modified version of the NEMS model used for the *Annual Energy Outlook 2009* (EIA 2009) to study gasoline taxes, the proposed Pavley standards, and two feebates.

2. Background on CAFE Standards and Feebates

2.1 CAFE Standards

CAFE standards were promulgated in the United States with the passage of the Energy Policy and Conservation Act of 1975. The first CAFE standard went into effect in 1978 and since that time the standards have undergone several changes, with the most dramatic changes in recent years. While on the surface CAFE standards appear to be a very simple regulation, in fact there are many important details that make the regulation much more complicated than just a minimum standard on the production-weighted harmonic average fuel economy for each manufacturer's fleet for a given model year.[2] While the regulation began as a standard only on passenger cars, within a year a separate, less stringent, standard was placed on each manufacturer's light truck fleet. Sport utility vehicles are included as light trucks, but any vehicle with a gross vehicle weight rating over 8,500 pounds was classified as a heavy duty truck and was exempt from the regulation.

The two-fleet format changed dramatically in 2011 with the introduction of standards based on the vehicle "footprint," defined as the vehicle wheelbase times the average track width.[3] Vehicles with larger footprints are given a less stringent standard than vehicles with smaller footprints, following a mathematical formula. For example, the formula for model year 2012-2016 passenger cars and light truck fleets is given by

$$S_{jt} = 1/\min(\max\left(c_t\, FP_j + d_t, 1/a_t\right), \frac{1}{b_t}),$$

where S_{jt} is the fuel economy standard for vehicle j in year t with footprint FP_j (EPA/DOT 2010) The formula contains the parameters a_t, b_t, c_t, and d_t, which vary by fleet and over time as the footprint based standard is tightened. The target for 2017-2015 model year vehicles is even slightly more complicated:

[2] The harmonic average is used instead of the arithmetic average in order to base the policy on fuel consumed. There are technically three fleets: domestic passenger cars (vehicles manufactured in the U.S., not necessarily by a U.S. automaker), imported passenger cars, and light trucks. However, automakers often have a great deal of flexibility in where they source parts from, so increasing the U.S.-content of a vehicle in order to switch it between the two passenger car fleets in many cases is not difficult. CAFE standards have in the past and continue to exempt police and emergency vehicles.

[3] In parallel to the fuel economy standards under the purview of the Department of Transportation, the US Environmental Protection Agency has set CO_2 standards for new vehicles to correspond with the fuel economy standards. Technically the footprint is defined as "the product of the track width (measured in inches, calculated as the average of front and rear track widths, and rounded to the nearest tenth of an inch) times wheelbase (measured in inches and rounded to the nearest tenth of an inch), divided by 144 and then rounded to the nearest tenth of an square foot" (p. 25667, Federal Register 2010).

$$S_{jt} = \max(1/\min\left(max\left(c_t\, FP_t + d_t, \frac{1}{a_t}\right), \frac{1}{b_t}\right), 1/(\min\left(\max\left(g_t\, FP_t + h_t, \frac{1}{e_t}\right), \frac{1}{f_t}\right)),$$

where g_t, h_t, e_t, and f_t are additional parameters that again vary by fleet and over time (EPA/DOT 2012). Figure 1 panel (a) illustrates the 2012-2025 CAFE target curves for the passenger vehicle fleet and panel (b) illustrates the target curves for the light truck vehicle fleet. The curves indicate that there is only modest increase in the standard at first, followed by a rapid increase in the standard in later years, albeit with a minor slow-down just after 2017. The curves also underscore that cars and trucks with a small footprint will be held to a very different standard than those with large footprints.

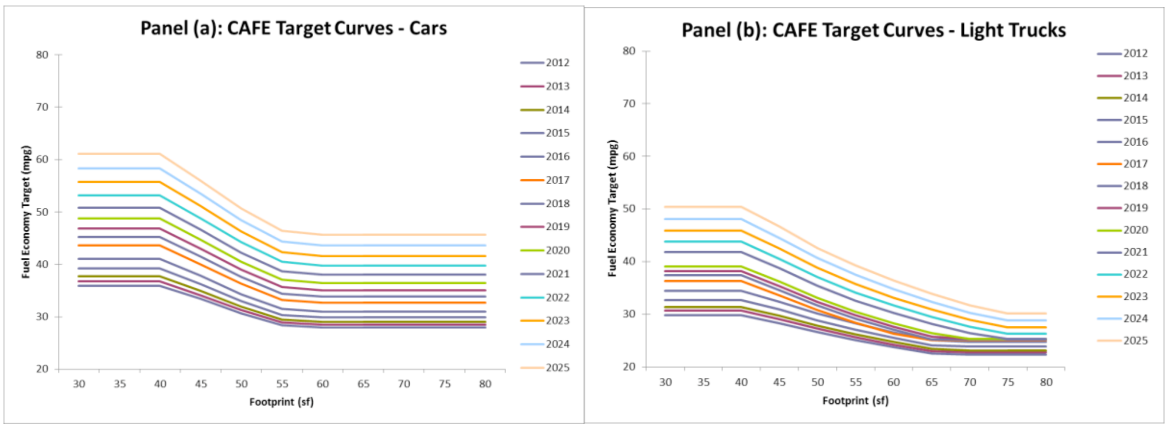

Figure 1. The CAFE fuel economy targets are less stringent with larger footprints, but increase in stringency over time. Panel (a) shows the CAFE targets for passenger cars and (b) shows the targets for light trucks.

An automaker is in compliance with the standard if the production-weighted harmonic average fuel economy in each fleet for each model year of vehicles exceeds the production-weighted harmonic average of the footprint targets (σ). More formally, this condition can be written as

$$\frac{\sum_j q_j}{\sum_j q_j/MPG_j} \geq \sigma = \frac{\sum_j q_j}{\sum_j q_j/S_j},$$

where q_j is the quantity of vehicle j produced MPG_j is the fuel economy in miles per gallon of the vehicle, and σ is the fleet-wide miles-per-gallon standard, which is equal to the production-weighted average of vehicle-specific standards based on the footprint of the vehicle.

This formulation of CAFE standards has the notable effect that automakers that produce cars or trucks with larger footprints will face a lower fleet-wide average target than those that produce smaller footprint cars. This is expected to be to the advantage of the large U.S. automakers, which tend to have larger vehicles than many of their competitors.

The shift to footprint-based standards was not the only change in 2011. Following suggestions laid out in the National Academy of Sciences report on CAFE standards (NRC 2002), since model year 2011 the CAFE regulation has contained provisions not only for banking and borrowing of credits for exceeding the standard, but also provisions for transferring credits between footprint categories, fleets, and even manufacturers. Automakers are permitted to carry-back credits from the current model year to make up for a deficit up to three years prior. Similarly, automakers can carry-forward credits earned from over-complying in a given model year up to five years afterwards. All of these provisions provide automakers with flexibility in meeting the standards and are designed to reduce manufacturer costs.[4]

There are yet further details of CAFE standards that merit attention. Perhaps most importantly, there is a provision in the regulation dating to the 1988 Alternative Motor Fuel Act (AMFA) that provides CAFE credits for automakers who produce vehicles that are capable of running on alternative fuels, such as ethanol. Flex-fuel vehicles that run on either E85 or gasoline are commonly used to exploit this provision. In fact, Anderson and Sallee (2011) even use the details of this provision to estimate the cost of CAFE standards. Looking forward, the flex-fuel vehicle credits will be phased out after model year 2019, but credits for dedicated alternative fuel vehicles will remain (Federal Register 2012).

In addition to the flex-fuel credit, CAFE credits are also granted for improving vehicle air conditioning units, for air conditioners contain potent greenhouse gases. Automakers can acquire CAFE credits for improving the efficiency of the air conditioning units, reduce refrigerant leakage or use alternative refrigerants. Similarly, there is an incentive multiplier for alternative fuel vehicles in the 2017-2025 standards: automakers producing electric vehicles, plug-in hybrid electric vehicles, fuel cell vehicles, and compressed natural gas vehicles can count each vehicle as more than one vehicle for compliance with the standards. For example, electric vehicles and fuel cell vehicles begin with a multiplier of 2.0 for model year 2017, which is phased down over time. All of the multipliers are set to expire in model year 2021.

There is another compliance mechanism as well: paying a civil penalty for violating the CAFE standard for any given fleet. The penalty is $5.50 (nominal dollars) for each for each tenth of a miles-per-gallon that an automaker's harmonic average fuel economy falls short of the standard, multiplied by the number of vehicles manufactured in that model year. In most years, only a handful of luxury automakers choose to pay the civil penalty rather than comply with the standard. The U.S. automakers have never paid the penalty, with the exception of Chrysler when it was DaimlerChrysler.

[4] The only caveat to this is that under the technically there is a cap for the maximum increase in fuel economy in each fleet that can be attributed to transferred credits. The EPA CO2 standards do not have this limitation.

Finally, in addition to the CAFE standard itself, there is also a "gas guzzler tax" on individual passenger cars. Begun in 1980, the gas guzzler tax started by fining vehicles with a fuel economy below 22.5 miles per gallon. The tax was revised in 1991, and it currently begins at $1,000 (nominal dollars) for vehicles with a fuel economy between 22.5 and 21.5 miles per gallon. It rises to $7,700 (nominal dollars) for vehicles getting less than 12.5 miles per gallon. The gas guzzler tax is not imposed on minivans, sport utility vehicles, or light trucks.

2.2 Feebates

In contrast to the current CAFE regulatory structure, feebates have the potential to be quite simple. While there are a variety of different possible structures for a feebate, the most common is a simple linear feebate that penalizes or rewards vehicles based on the difference between the vehicle's fuel consumption (in gallons per mile) and a "pivot point" fuel consumption. In this type of feebate program, the net transfer upon purchasing the vehicle is given by

$$F_j = R\left(\frac{1}{MPG_0} - \frac{1}{MPG_j}\right),$$

where R is the rate (in dollars per gallon per mile) that scales the policy and MPG_0 is the pivot point fuel economy (in miles per gallon). Just like CAFE standards, a feebate policy can be designed to be very close to revenue neutral. If the pivot point is set at the weighted average fuel economy of the entire fleet of vehicles produced in a model year, the policy would be revenue-neutral. In this case the revenue brought in from the fees would exactly offset the funds given out as rebates. Of course, the policy would have to be set in advance, so it is more likely that such a policy that the policy would be *close* to revenue-neutral. In order to continue to keep the policy close to revenue neutral, regulators would have to continually adjust the pivot point upwards over time as technology improves.

The feebate policy need not have a single rate and single pivot point. In fact, much like CAFE standards, the feebate policy could have a separate pivot point for each fleet and even a separate rate for each fleet. Finally, the point of regulation for the feebate may be on either the manufacturer or consumer side, although most recent implementations have the point of regulation on the consumer.

3. Framework for Understanding CAFE Standards and Feebates

This section presents a set of analytical results to elucidate the similarities and differences between CAFE standards and feebates. Roth (2012) and Klier and Linn (2012) present analytical results indicating that a simple fuel economy standard can be equivalent to a feebate. The results here formalize this further by deriving how to design a feebate to exactly match a *multi-fleet tradable* CAFE standard. Furthermore, the results highlight when the two policies differ, emphasizing how important the details of the regulation are for the performance of the policy instrument. The similarities and differences are presented in the context of the cost-effectiveness of the policies to meet a particular fleet-wide MPG goal. The economic efficiency of both policies is discussed in section 3.4.

3.1 Incentives provided by CAFE Standards

Under CAFE standards, the automaker chooses vehicle prices and attributes to maximize profits subject to the CAFE standard constraint or set of constraints. To simplify, consider a two period problem, where the first time period is the vehicle development stage and the second time period is the production and sales stage. The manufacturer chooses the attributes of the vehicle in the first stage and chooses the price in the second stage. This can be thought of as a model of Bertrand differentiated products competition, yet an analogous derivation would apply in other models of competition, including perfect competition. For the purposes of building intuition, I am assuming no discounting and no uncertainty.

Begin with a fixed CAFE constraint σ_k for each of the manufacturer's vehicle fleets *k* in a model year. The constraint that each manufacturer must meet is given by $\frac{\sum_{j \in J_k} q_j}{\sum_{j \in J_k} q_j / MPG_j} \geq \sigma_k$, where J_k is the set of vehicles in fleet *k*. This constraint can also be rewritten more simply as $\sum_{j \in J_k} [q_j (1 - \sigma_k / MPG_j)] \geq 0$. To begin, assume there is no trading, banking or borrowing permitted.

The manufacturer's problem for each vehicle *i* in the entire set of vehicles J can be written as:

$$\max_{p_i, \theta_i} -R_i(\theta_i) + \sum_{j \in J} p_j q_j(p_i, \theta_i) - C_j(q_j, \theta_j)$$
$$s.t. \sum_{j \in J_k} [q_j (1 - \sigma_k / MPG_j)] \geq 0 \quad \forall\, k$$

where $R_i(\theta_i)$ are the research and development (R&D) costs of the vehicle with attributes given by the vector θ_i, p_i is the price of vehicle *i*, and C_j is the total cost of producing q_j of vehicle *j* with attributes θ_j. This formulation abstracts from the alternative fuel credits, gas guzzler tax, and the civil penalty. It also assumes that the non-negativity constraints for prices and quantities are not binding.

The Lagrangian for this problem is

$$L = -R_i(\theta_i) + \sum_{j\in J} p_j q_j(p_i, \theta_i) - C_j(q_j, \theta_j) + \sum_k \lambda_k \sum_{j\in J_k} [q_j(1 - \sigma_k/MPG_j)]$$

where λ_k is the shadow price on the CAFE constraint in each fleet *k*, or the marginal profits from relaxing that CAFE constraint. The first order conditions are as follows:

$$\sum_{j\in J} p_j \frac{\partial q_j}{\partial p_i} + q_j + \sum_k \lambda_k \sum_{j\in J_k} \frac{\partial q_j}{\partial p_i}(1 - \frac{\sigma_k}{MPG_j}) = \sum_{j\in J} \frac{\partial C_j}{\partial q_i}\frac{\partial q_j}{\partial p_i}$$

$$\sum_{j\in J} p_j \frac{\partial q_j}{\partial \theta_i} + \sum_k \lambda_k \sum_{j\in J_k} \frac{\partial q_j}{\partial \theta_i}\left(1 - \frac{\sigma_k}{MPG_j}\right) = \sum_{j\in J} \frac{\partial C_j}{\partial \theta_i} + R_i' \quad \forall\, \theta_i \neq MPG_i$$

$$\sum_{j\in J} p_j \frac{\partial q_j}{\partial MPG_i} + \sum_k \lambda_k [\sum_{j\in J_k} \frac{\partial q_j}{\partial MPG_i}\left(1 - \frac{\sigma_k}{MPG_j}\right) + \frac{\sigma_k q_i}{MPG_i^2}] = \sum_{j\in J} \frac{\partial C_j}{\partial MPG_i} + R_i'$$

The first of the three first order conditions indicates that manufacturers price each vehicle so that the influence of a marginal change of the price on revenues for the sale of all vehicles in the manufacturer's fleet plus the effect of a marginal change of the price on the manufacturer meeting the CAFE standard is equal to the change in total cost when the price changes. The primary insight from this first equation is that profit-maximizing automakers will take into account how changing the price of any given vehicle influences whether each fleet *k* is going to meet the CAFE standard.

The second and third first order conditions relate to the choice of the attributes of the vehicle. They both indicate that the additional revenue from the sale of all new vehicles in the fleet with a marginal change in the attribute plus the effect on meeting the CAFE standard from a marginal change in the attribute must be set equal to the marginal change in production and R&D cost with a change in the attribute. These two equations are quite intuitive: the automaker will continue to improve attributes (including fuel economy) until the additional gains from doing so are equal to the costs. Note that for many attributes and other vehicles *j*, we may have $\frac{\partial q_j}{\partial \theta_i} < 0$, for improving the attributes in vehicle *i* may lead to cannibalization of the sales of vehicle *j*. Thus, the choice of attributes for any one vehicle is a complex decision involving the consequences on the sales of all of the rest of the vehicles.

The shadow price on the CAFE standard in each fleet λ_k plays a key role in mediating the effect of the standards. If the production-weighted average fuel economy for an automaker in fleet *k* is greater than σ_k, then the standard does not directly affect the firm's decision-making and $\lambda_k = 0$. Otherwise, the automaker chooses the prices and attributes of the vehicle by weighing how these choices will affect meeting the standard and $\lambda_k > 0$. This will hold regardless of how many fleets there are. If there was a single fleet, then there would be a single σ, and thus a single λ.

Note that this would be more efficient than multiple shadow prices, for if the shadow price differs across the fleets, there would be opportunities to reduce fuel consumption at a lower cost by tightening the standard in one fleet and relaxing it in another.

With trading between fleets, the situation changes. Automakers can improve the weighted-average fuel economy more in one fleet, where it is less costly, in order to acquire CAFE credits that can then be transferred to another fleet that is below the fuel economy standard. Then there would be a single λ again. As long as the automaker does not have a surplus of credits (i.e., $\lambda = 0$), then there would be continual incentives to improve fuel economy. Moreover, if there is trading between automakers, then there would not only be a single λ for all fleets of each automaker, there would be a single λ across all automakers.

With banking and borrowing of CAFE credits, λ will be equilibrated over time as well, for automakers can improve the fuel economy of their vehicles more than the standard in one year and bank the credits for use in a later year. With partial banking and borrowing, as in the latest CAFE regulation, λ will be partially equilibrated over time, which prevents automakers from building up a large stockpile or deficit of CAFE credits.

Most of the remaining details of the current CAFE standards, such as the alternative fuel vehicle credits and air conditioning credits, primarily serve to relax the CAFE constraint σ. One exception is the civil fine for violating the constraint. The automakers paying the fine simply face a penalty or tax that is scaled by the difference between the harmonic average fuel economy and the standard. Put differently, for each fleet profits would be reduced by $\$55 \sum_j [q_j(1 - \sigma_k / MPG_j)]$. The first order conditions would again be identical, only with $\lambda_k = \$55$. Since one would expect profit maximizing firms to use the least expensive method to comply – pay the fine or adjust prices and attributes – it is possible to interpret $55 as the upper bound on the cost of CAFE. However, as described in Jacobsen (2012), there may be sufficiently high public relations costs that the U.S. automakers would have to bear for paying the civil fine and not complying that the upper bound may in fact be higher than this.

3.2 Incentives provided by Feebates

Under feebates, there is either a fee charged or a rebate given for each vehicle. The point of regulation can be either at the manufacturer level or more directly at the point-of-sale. Most feebates that have been implemented are at the point-of-sale. I will first model a feebate at the manufacturer level and then will discuss a point-of-sale feebate.

Consider a feebate $F_j(MPG_j)$. The automaker again chooses attributes and prices to maximize profit for a given vehicle i. I again assume no discounting and no uncertainty. The automaker's problem for each vehicle i in the set of vehicles J can be written as:

$$\max_{p_i,\theta_i} -R_i(\theta_i) + \sum_{j\in J}[p_j + F_j(MPG_j)]q_j(p_i,\theta_i) - C_j\big(q_j,\theta_j\big).$$

The first order conditions are as follows:

$$\sum_{j\in J}[p_j + F_j]\frac{\partial q_j}{\partial p_i} + q_j = \sum_{j\in J}\frac{\partial C_j}{\partial q_i}\frac{\partial q_j}{\partial p_i}$$

$$\sum_{j\in J}[p_j + F_j]\frac{\partial q_j}{\partial \theta_i} = \sum_{j\in J}\frac{\partial C_j}{\partial \theta_i} + R_i' \quad \forall\, \theta_i \neq MPG_i$$

$$\sum_{j\in J}([p_j + F_j]\frac{\partial q_j}{\partial MPG_i} + \frac{\partial F_j}{\partial MPG_i}q_j) = \sum_{j\in J}\frac{\partial C_j}{\partial MPG_i} + R_i'$$

These first order conditions have a similar interpretation to the first order conditions under CAFE standards. The first condition suggests that manufacturers will adjust prices, taking into account the feebate, such that the marginal benefit of increasing the price is equal to the marginal cost. The second and third conditions indicate that automakers will improve attributes to the point where the marginal benefits, based on the market with feebates, is equal to the marginal cost. For fuel economy, the marginal effect on the size of the feebate is also considered, indicating how there is a continual incentive to improve fuel economy, even for high fuel economy fleets.

What if there are multiple pivot points corresponding to different fleets? For example, there could be a different pivot point for the passenger car fleet as the light truck fleet. With multiple pivot points, the first order conditions would be identical to those above. The only difference would be that F_j would be defined differently for each vehicle based on the fleet it is in, with a different pivot point and/or rate for each fleet. In this case, the feebate for vehicle j in fleet k can be written as

$$F_j = R_k\left(\frac{1}{MPG_{0k}} - \frac{1}{MPG_j}\right).$$

Suppose the point of regulation of the feebate was directly on consumers, rather than at the manufacturer level. In this case, firms would be paid p_i rather than $p_i + F_i$ for vehicle i, but the demand $q_i(p_i,\theta_i)$ would be changed to $q_i(p_i + F_i,\theta_i)$. Under standard economic theory, the equilibrium outcome will be the same regardless of the point of regulation. The intuition is simple: if the point of regulation is on the manufacturer side, at least some portion of the additional subsidy or fee will be passed along to consumers, while if the point of regulation is on the consumer, automakers will adjust prices leading to an identical result.

The only caveat is that there is some evidence from the recent behavioral economics literature that consumers respond more to *salient* prices and incentives than to those passed-through. For example, Chetty, Looney, and Kroft (2009) find that consumer demand decreases when sales taxes are included on the sticker price rather than at the register – even though surveyed consumers were fully aware of the sales tax rate. Chetty, Looney, and Kroft attribute this finding to the sales tax being more salient when it is on the sticker price. It is possible that when the feebate is faced by the consumer, the feebate will have a greater impact on the demand for different vehicles because it is more visible. Alternatively, a feebate on consumers may also have a greater impact if there are rigidities in pricing, although these can be expected to be dissipated in the long run. Should either of these be true – and there is currently no evidence they are – then a feebate on consumers may lead to a different result than a feebate on manufacturers. In this case, one might expect the feebate on consumers to have a greater impact on the demand for vehicles, leading the feebate policy to be more effective (and possibly cost-effective). Given the lack of empirical evidence on this issue, the numerical component of this paper considers the point of regulation irrelevant and implements the feebate on consumers, leading to an indirect incentive for manufacturers to change vehicle attributes.

3.3 When are CAFE Standards and Feebates Equivalent?

The incentives provided by CAFE standards and feebates turn out to be strikingly similar – with some caveats. I formalize this in a series of propositions.

Proposition 1. A CAFE standard policy that is binding on all manufacturers and contains no banking or borrowing of CAFE credits, no trading of CAFE credits, no CAFE credits for alternative fuels or air conditioning improvements, no civil penalties, and no gas guzzler tax provisions can be made exactly equivalent to a linear feebate policy. Furthermore, the equivalence is obtained with the pivot points defined by $MPG_{0k} = \sigma_k$ and the rates defined by $R_k = \lambda_k \sigma_k$.

The proof of this proposition is by equivalence of the first order conditions and is contained in the appendix. This proposition holds regardless of the number of fleets and regardless of whether the standard is a footprint based standard or not. The proposition provides a way to map CAFE standards directly into a linear feebate.[5]

The following corollary is more relevant to CAFE standards going forward, since CAFE credit trading is an integral part of the current legislation.

[5] In contrast, not every feebate can be mapped back to CAFE standards, for the rate of the feebate would have to equal the shadow price of the standard times the pivot point for the two to be equivalent.

Corollary 1. If trading across fleets is permitted, the result in Proposition 1 continues to hold, with the pivot points defined by $MPG_{0k} = \sigma_k$ and the rates defined by $R_k = \lambda\sigma_k$.

Corollary 1 follows directly from the fact that trading leads to a single λ across fleets. It indicates that if there are multiple fleets in a CAFE standard policy, an equivalent feebate must have multiple fleets as well.

Both findings rely on CAFE standards that are binding on all manufacturers and all fleets. With trading between manufacturers, there is a single λ across all manufacturers, so unless the CAFE standards are so easy to meet that $\lambda = 0$, Corollary 1 holds. Without trading, the CAFE constraint may not be binding for some manufacturers that produce only relatively high fuel economy vehicles (e.g., Honda and Toyota during many years in the past few decades). In this case, the high fuel economy manufacturers would have no direct incentive from the policy to improve fuel economy further, a stark contrast from the feebate policy.

While the analysis above looks at static incentives, when we look at intertemporal compliance, CAFE standards can again be made to be equivalent to feebates by including banking and borrowing. The intuition is simple. If the costs of improving fuel economy (either sales or engineering costs) turn out to be unexpectedly high in a particular year for an automaker, then the automaker will improve fuel economy less in a particular year and just face a higher fee (or receive a lower rebate). If the costs turned out to be low, the automaker would unveil an even more efficient vehicle and would reap a higher rebate (or lower fee). Thus, the policy is dynamically efficient by construction. This would not be the case for CAFE standards without banking and borrowing, for the automaker would have to meet the standard (with the caveat of the civil penalty). With banking and borrowing, firms will have intertemporal compliance flexibility, so that if the cost is unexpectedly high (low) in a given year, firms can borrow (bank) permits and improve the fuel economy less (more), lowering (increasing) the costs in that year. If the two policies are designed so that the static incentives match and banking and borrowing is permitted for the CAFE standards, then the two policies could both be cost-effective in a dynamic setting.

Finally, feebates could be designed with the option of paying a fine rather than complying with the feebate. This would allow the feebate to more closely match the current CAFE regulation. Alternatively, the pivot point and rate of the feebate could be adjusted based on the granting of alternative fuel or air conditioning CAFE credits, just as in the current CAFE regulation. Of course, while many of these details in the CAFE policy could be replicated in a feebate, they do add significant complexity to the policy, reducing the transparency and potentially the cost-effectiveness of the policy.

3.3 Footprint-based CAFE Standards and Feebates

The above proposition assumes a fixed CAFE standard for each fleet. Automakers can choose to produce more vehicles in the fleet with the less stringent standard, but cannot change the standard itself. Under a footprint-based CAFE standards, the standard for each fleet itself can be changed through the choice of the footprint. Recall that under the footprint based standard,

$$\sigma_k = \frac{\sum_{j \in J_k} q_j}{\sum_{j \in J_k} q_j / S_j(FP_j)}.$$

This leads to the following straightforward proposition.

Proposition 2. Under a footprint-based CAFE standard, automakers will strictly increase vehicle footprints relative to a non-footprint based CAFE standard.

The intuition for the proof of this proposition is simple: by increasing the footprint of vehicle i, the automaker can relax the standard for that vehicle. A proof is included in the appendix. Note that the incentives here are entirely analogous to the incentives created by the two-fleet rule, where the standard that applies to any vehicle depends on whether the chassis is a light truck or car chassis.[6] Surprisingly, this proposition still holds even if it is costly (either in sales or engineering cost) to increase the footprint.

The next proposition shows that if a feebate includes a pivot point for each footprint, the same result holds.

Proposition 3. Under a feebate policy with a pivot point for each footprint, automakers will strictly increase vehicle footprints relative to a non-footprint feebate.

The logic behind this proof is the same as for Proposition 2; the proof is included in the appendix. Interestingly, this proposition also indicates that even if there are only two pivot points, there would be an incentive to change vehicle attributes so the lower pivot point applies.

When combining Propositions 2 and 3 with the result in Proposition 1, we can see that a feebate policy with a pivot point for each footprint creates very similar incentives to a footprint-based CAFE standard. Yet the two are slightly different and finding a set of pivot points and rates for a feebate policy to exactly match the incentives of a footprint-based CAFE standard would likely be possible, but quite difficult. Moreover, given that upsizing the fleet may lead to concerns

[6] The Chyrsler PT Cruiser is a perfect example of a car built on a truck chassis, which allowed it to qualify as a light truck under CAFE standards.

about safety (Jacobsen 2012), it is unlikely that such a feebate would be desirable. These findings highlight the perverse incentives created by a footprint based standard.[7]

3.4 Economic Efficiency of CAFE and Feebates

The above discussion demonstrates that both CAFE standards and feebates can provide very similar incentives to firms and that the details of the policies are critical. A carefully designed feebate can lead to nearly identical outcome as a particular CAFE standard policy, even if the feebate does not explicitly guarantee a particular minimum average fuel economy of new vehicles. Both CAFE standards and feebates can achieve greater cost-effectiveness by being designed with a single λ across manufacturers and fleets (either through trading or a careful choice of the rate of the feebate policy).

Both CAFE standards and feebates have an identical weakness: they only affect new vehicle purchases. Energy use and emissions are from the driving of the entire stock of vehicles on the road. By improving new vehicle fuel economy, both policies mean that driving is less expensive per mile, thus leading to more driving – an effect known as the rebound effect. Analysts commonly use estimates of the elasticity of driving with respect to the cost of driving (or the gasoline price) as a benchmark for the rebound effect. These estimates hover in the range of -0.1 to -0.2 in the short and medium run, and a bit higher in the long run, suggesting that some 10 to 20 percent of the fuel savings from CAFE standards or feebates may be countered by increased fuel use from more driving (Gillingham 2011).

In addition to the rebound effect, both CAFE standards and feebates would likely lead to automakers including new fuel-saving technologies in new vehicles, adding to the cost of the new vehicles (recall the incentives for pricing can be identical under the two policies). With more expensive new vehicles, consumers may hold on to older low fuel economy vehicles longer. This effect has been addressed as part of larger studies of CAFE standards (e.g., Bento et al. 2009), but has not been studied in detail. It is fair to say that the effect exists, but reliable estimates are as of yet elusive.

For these reasons, CAFE standards have commonly been considered by economists as a "second-best" policy option that may be more politically feasible, but less economically efficient than a policy such as a gasoline tax that addresses new vehicle purchases, driving, and scrappage of old vehicles. Feebates would face the same critique. However, recent research suggesting that

[7] One argument for footprint-based standards in the presence of CAFE credit trading across manufacturers is that manufacturers that have a high fuel economy fleet, such a Honda and Toyota, would be net sellers of the credits, while many of the U.S. manufacturers would net purchasers. Under a feebate, a single fleet feebate may be more politically feasible because it would make the transfers between firms less transparent, in the sense that high fuel economy vehicles would receive greater rebates than low fuel economy vehicles, but there would be no explicit transfers between firms. However, domestic automakers may continue to express concern unless other policy mechanisms are in place to compensate them.

consumers may "undervalue" the vehicle attribute of fuel economy relative to other choices they make may entirely change this story (Allcott and Wozney 2012). This effect is also sometimes described as "consumer myopia" or "high implicit discount rates." Not all recent studies find evidence of consumer undervaluation (e.g., Busse et al. 2013), and all of the studies have wide bands of possible degrees of undervaluation based on a variety of relatively poorly understood parameters. However, if such undervaluation does exist, then policies such as standards may make consumer ex post happier by inducing them to buy a higher fuel economy car. Allcott et al. (2012) suggest that a concept from behavioral economics, "inattention," may help explain why consumers appear to care less about fuel economy than might be expected. If such concepts from behavioral economics can be rigorously applied to the vehicle purchase decision, it is possible that CAFE standards – and feebates – may have additional welfare benefits that a gasoline tax would not. In this case, the conventional wisdom that CAFE standards and feebates would be unequivocally "second-best" policies may not hold. Yet this is still a very active area of research and it is probably too soon to reach a definitive verdict.

4. Analysis of CAFE Standards and Feebates Using NEMS-NEPI

The previous section provided an analytical grounding for better understanding how CAFE standards and feebates work. The results clarified the similarities between the two policies and pointed to a few minor differences. This section numerically explores the effects of CAFE standards and feebates using the NEMS-NEPI model.

4.1 Brief Description of NEMS

NEMS is an energy-economy market equilibrium model with considerable detail on the energy sector of the economy designed to analyze the effects of U.S. government policies out to 2030. The model contains a variety of interacting modules covering the key sectors of the economy, with exceptional detail in the most relevant areas for energy and climate policies. For this reason, NEMS is the primary modeling tool used by DOE for a variety of energy and climate projections and policy analyses – including analyses of national transportation policies such as fuel economy standards. NEMS captures energy supply, conversion, demand, as well as interactions between the domestic energy system/economy and the world energy market. It contains 9 regions of the United States, as shown in Figure 2.

Figure 2. NEMS divides the United States into nine regions. Source: EIA (2009b).

Figure 3 provides an overview of the interactions between the different modules of the NEMS model. This brief overview of the NEMS model will focus on the most relevant details of the transportation demand module for this study. One advantage of the NEMS is that it is extremely well documented, and I refer readers interested in the other modules to the official NEMS documentation (EIA 2009).

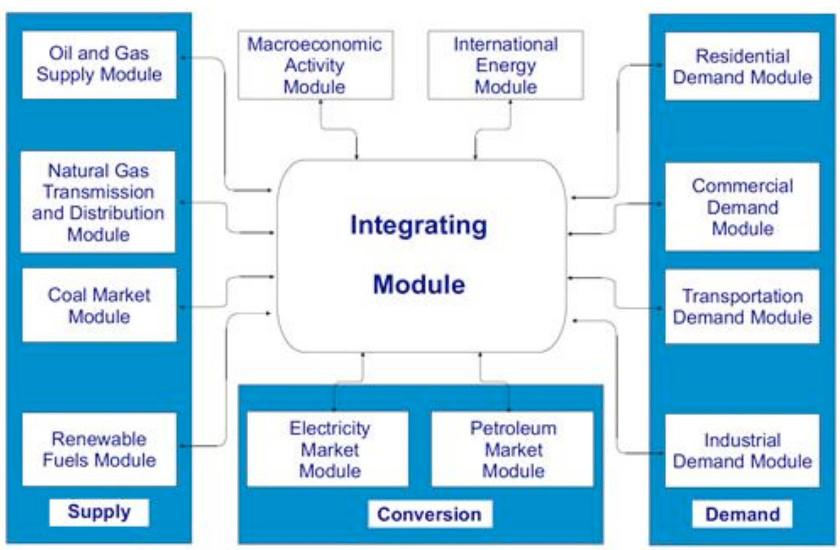

Figure 3. This schematic shows the different modules of the NEMS model. Source: EIA (2009).

In the transportation demand module, the light duty vehicle fleet is modeled with the greatest detail. Following CAFE standards, the light duty fleet contains a car fleet and light truck fleet, each of which are divided into six size classes. For cars these are mini-compact, compact, subcompact, midsize, large, and two-seater sports cars, while for trucks these are small and large

SUVs, small and large pickups, and small and large vans. Rather than modeling each manufacturer explicitly, NEMS models the automakers in a stylized fashion by grouping the manufacturers into domestic car manufacturers, imported car manufacturers, three domestic light truck manufacturers, and two domestic light truck manufacturers. The vehicles produced must use one of 16 fuel types, with gasoline electric, and diesel electric included as separate fuel types from conventional gasoline (EIA 2008).

NEMS models the evolution of the light duty fleet in three steps. First, manufacturers choose which technologies to adopt for a given fuel type, out of a very large suite of potential technologies (including many that are not currently in use). The technologies improve over time as they become adopted, following a learning-by-doing relationship. Manufacturers choose technologies based on the cost-effectiveness of the technologies: whether consumers who consider a three-year payback period and discount at an interest rate of 15 percent would purchase the vehicles.[8] In a sense, this can be thought of as a model of the manufacturer's vehicle technology choices given expectations of future new vehicle purchase behavior. Once the technologies are chosen, the set of vehicles (and their characteristics) available within each size class and fuel type is fixed. The price of the vehicle is fixed at this point and is assumed to be the production cost plus any feebate or CAFE fine.

Second, consumers choose the share of cars and light trucks, and within each of these, the market shares of each of the fuel types. The shares of cars and light trucks are chosen using a logit-like formula where the change in market shares is modeled as a function of key variables such as the change in fuel prices, income, and new vehicle fuel economy (Small 2010). The market shares are chosen based on an aggregate nested logit model. The first nest has conventional vehicles compete against hybrid electric vehicles, natural gas vehicles, fuel cell vehicles, and electric vehicles. The next stage models competition within each of these groups. For example, within conventional vehicles, gasoline, diesel, flex-fuel ethanol, and bi-fuel natural gas vehicles compete. This competition is based on characteristics such as vehicle price, fuel cost, vehicle range, acceleration, maintenance cost, luggage space, fuel availability, and diversity of makes and models in the group. The coefficients used in the nested logit differ for each vehicle class and are calibrated to match known market shares in recent years. Some of these coefficients vary over time corresponding to EIA's expectations of future consumer preferences (EIA 2008).

Third, the stock of vehicles is adjusted in each year by the flow of new vehicles into the stock and the flow of scrapped vehicles out of the stock. NEMS models scrappage with exogenous vehicle survival rates. Driving is modeled as a function of income and the fuel cost per mile driven and exogenously divided up for each vintage of vehicles (EIA 2008).

[8] As noted in Small (2010), this assumption of consumer undervaluation of fuel economy may be at least partly countered by the assumption that consumers project gasoline prices based on trends observed over the past eight years, rather than current price as is indicated in Anderson et al. (2011).

The NEMS framework has several important advantages for modeling policies that influence future vehicle fleets. NEMS' detailed representation of technology rivals nearly all other models of vehicle fleets, allowing for realistic future scenarios. Similarly the disaggregation of fuel types and vehicle classes is extremely useful for examining policies that lead to changes in the composition of the fleet. The integration of the transportation module into the full NEMS framework puts transportation in the context of the overall energy system in a way not possible in many modeling frameworks. For this study, NEMS is slightly modified to create the NEMS-NEPI model in collaboration with OnLocation (http://www.onlocationinc.com/). The primary modification relevant to this study is the development of a framework for modeling a feebate; otherwise the results from AEO 2012 can be replicated.

Despite its advantages, the light-duty fleet modeling using NEMS-NEPI has some limitations. Used car markets are not modeled at all. Automakers are assumed to pass through all increases in costs to consumers. This simplistic assumption prevents changes in prices to increase or decrease the automaker's mark-up in response to how regulation changes the competitive structure of the industry. With no price adjustment (effectively assuming away the first of the three first order conditions for CAFE standards and feebates), automakers are assumed to adjust to regulation primarily by adding technology. It is possible that this realistically matches how the new vehicle market works, but research has yet to convincingly demonstrate it (Small 2010).[9] Finally, NEMS-NEPI makes many assumptions about consumer preferences and automaker expectations of consumer preferences. The coefficients determining the share of each fuel type are exogenously set and thus are not adjusted by policy. Automakers are assumed to choose the characteristics of the vehicles they offer based on the assumption that consumers undervalue fuel economy. This may realistically model past manufacturer behavior, but it is an exogenous assumption that would not change even if there were dramatic increases in the gasoline price that could increase consumer interest in fuel economy. These limitations imply that any NEMS-NEPI results should be taken in context and considered most useful for qualitative insights.

4.2 Primary Model Results

For this study, I run three primary scenarios: the AEO 2012 reference case, the recently enacted CAFE standards, and a nearly revenue-neutral feebate case designed to match the CAFE standards after 2017. The feebate policy is assumed to replace the CAFE standards in 2017, with the beginning of the 2017-2025 standards. The primary feebate modeled contains a single pivot point for each model year.[10] With the exception of the implementation of the CAFE and feebate

[9] Incidentally, this author has preliminary results from work-in-progress indicating that most of the adjustment by firms in response to CAFE standards is indeed in the vehicle attributes, with only very limited adjustment in prices.
[10] Additional robustness checks show that the results are extremely similar if multiple pivot points are used. This is analogous to the similar results in NEMS with a two-fleet standard or a two-fleet footprint-based standard. While

policies, all other assumptions in the model match the *AEO 2012*, so they are based on the very latest projections. In fact, the CAFE standards run exactly matches the *AEO 2012* CAFE standards simulation, designed to replicate the issued CAFE standards as closely as possible. The new vehicle harmonic average fuel economy in the baseline and the three scenarios is shown in Figure 4.

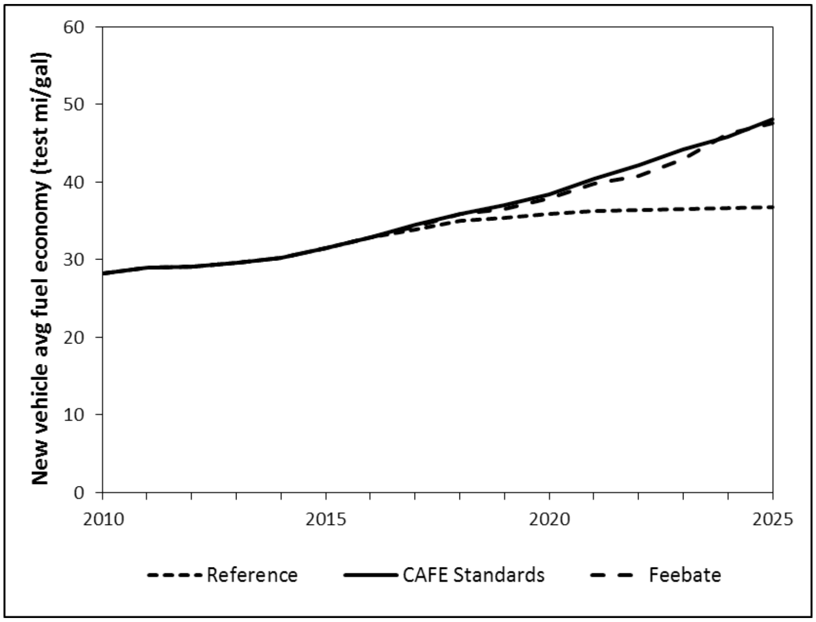

Figure 4. – The harmonic mean fuel economy across all vehicles is very similar between the CAFE standards and feebate cases, both of which show improvements above the reference case.

All three simulations show an increase in test fuel economy over time. The CAFE standards and feebate simulations are very closely matched – highlighting how a feebate policy can be designed to very closely replicate the results of the CAFE standard. Neither meets the 54.5 miles per gallon set out in the latest CAFE standards for 2025 because these values do not include any CAFE credits for alternative fuel vehicles or air conditioning improvements, just as in AEO 2012. Table 1 shows the feebate rate, pivot point, average achieved miles per gallon, and revenue collected each year from the feebate policy.

Table 1. Details of the feebate policy with a single pivot point

Year	Feebate rate (2010$/gal/mi)	Pivot point (mi/gal)	Achieved fuel Economy (mi/gal)	Revenue raised (billion 2010$)
2017	67,000	33.7	34.2	-0.01
2018	83,750	35.4	35.9	0.00
2019	104,688	36.0	36.5	-0.01
2020	130,859	37.3	37.9	0.00

NEMS-NEPI captures many of the incentives of automakers, the structure is not designed to model an upsizing response to regulation.

2021	163,574	39.3	39.8	0.03
2022	204,468	40.3	40.8	0.07
2023	255,585	42.4	43.0	0.07
2024	319,481	45.6	46.2	0.19
2025	319,481	47.1	47.6	0.42

As shown in Table 1, the feebate policy is very nearly revenue-neutral. The magnitude of the feebate begins at a relatively modest level; in 2017, a new vehicle getting 40 mi/gal would receive $313 (all dollars hereafter in 2010$), while a new vehicle getting 20 mi/gal would have a fee assessed of $-1,361. The feebate ramps significantly, so that by 2025, a new vehicle getting 40 mi/gal would receive $1,493, while a new vehicle getting only 20 mi/gal would have a whopping fee of $-6,493. Table 2 assembles the key results from each of the simulations in 2015, 2020, and 2025.

Table 2. Key light-duty vehicle (LDV) fleet results from the reference, CAFE standards, and feebate runs.

	Reference			CAFE standards			Feebate		
	2015	2020	2025	2015	2020	2025	2015	2020	2025
New LDV Fuel Economy (mi/gal)	31.52	35.90	36.80	31.53	38.41	48.07	31.53	37.86	47.60
Cars	36.43	40.30	41.35	36.43	44.79	55.65	36.43	43.12	56.48
Light Trucks	26.74	30.63	30.96	26.74	31.45	39.56	26.74	31.82	38.27
New Vehicle Price (000s 2010$)	26.53	27.11	27.14	26.53	27.71	29.27	26.52	27.69	29.37
Cars	25.59	26.21	26.31	25.58	27.00	28.39	25.58	26.49	27.77
Light Trucks	27.78	28.54	28.59	27.78	28.82	30.82	27.78	29.56	31.86
LDV Sales Shares by Fleet (%)									
Cars	57.1	61.2	63.2	57.1	60.8	61.2	57.1	60.8	60.8
Light Trucks	42.9	38.8	36.8	42.9	39.2	38.8	42.9	39.2	39.2
LDV Sales Shares by Fuel Type (%)									
Conventional Gasoline	79.6	75.6	73.0	79.6	75.4	69.7	79.7	71.5	61.7
% microhybrids of Gasoline	2.2	9.0	8.6	2.2	20.7	48.5	2.2	13.8	39.5
Conventional Diesel	4.1	4.3	4.3	4.1	4.0	4.6	4.1	5.7	5.4
% microhybrids of Diesel	0.8	3.3	3.3	0.8	18.0	49.2	0.8	4.9	19.6
Ethanol Flex-Fuel	12.4	14.8	15.8	12.4	14.9	16.4	12.4	14.5	14.9
Electric-Gasoline Hybrid	2.8	3.5	3.8	2.8	3.6	4.2	2.8	5.1	6.3
Electric-Diesel Hybrid	0.0	0.0	0.6	0.0	0.0	1.1	0.0	0.1	1.4
Plug-in HEV10	0.3	0.5	0.6	0.3	0.6	1.3	0.3	0.8	1.4
Plug-in HEV40	0.2	0.5	0.6	0.2	0.6	0.6	0.2	1.0	1.7
Dedicated EV	0.0	0.3	0.8	0.0	0.4	1.7	0.0	1.0	6.8
Total New Vehicle Sales (millions)	15.36	15.54	16.83	15.36	15.43	16.46	15.35	15.55	16.90
Total VMT (billions)	2,710	2,882	3,116	2,710	2,882	3,129	2,710	2,883	3,134
LDV Stock Fuel Economy (mi/gal)	21.5	23.6	25.6	21.5	23.8	27.5	21.5	23.8	27.2
Total LDV Energy Use (quad Btu)	15.4	14.8	14.8	15.4	14.7	13.8	15.4	14.7	13.9
Motor Gasoline	15.2	14.4	14.0	15.2	14.2	12.9	15.2	14.2	12.9
Diesel	0.2	0.3	0.4	0.2	0.3	0.4	0.2	0.3	0.5
E85	0.0	0.1	0.3	0.0	0.1	0.4	0.0	0.1	0.4
Electricity	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Other Fuels	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.1	0.1
Oil and Gasoline									
Oil Imports (mil bbl/day)	8.28	7.07	7.13	8.28	6.98	6.63	8.29	7.02	6.70
Liquid Fuel Cons (mil bbl/day)	19.15	19.12	19.33	19.15	19.03	18.77	19.15	19.07	18.84
Crude Oil Price (2010$/bbl)	117	127	133	117	126	131	117	126	131
Motor Gasoline Price (2010$/gal)	3.54	3.69	3.82	3.54	3.70	3.71	3.54	3.69	3.77
Energy-Related GHG Emissions									
Transport (mil metric t CO2-e)	1,865	1,827	1,822	1,864	1,815	1,751	1,864	1,819	1,760
All Sectors (mil metric t CO2-e)	5,411	5,447	5,579	5,405	5,432	5,498	5,404	5,435	5,518
GDP (trillions 2010$)	16.43	18.58	21.30	16.43	18.58	21.31	16.43	18.58	21.32

Notes: “mil” stands for million, “quad” stands for quadrillion, “bbl” stands for barrels, “CO2-e” stands for carbon dioxide equivalent.

Table 2 highlights several points. First both the CAFE standards and feebate simulations reach very similar outcomes on all of the broad indicators. Both lead to approximately 30% greater new vehicle fleet fuel economy by 2025. Gasoline consumption is reduced by 7.6% in both cases. Oil imports are reduced by around 6% and overall liquid fuel consumption by just under 3%. Similarly, total transportation greenhouse gas emissions are reduced by about 3% in both cases. The total amount driven by all vehicles in the light-duty vehicle fleet increases under both policies, indicating a small overall rebound effect from the policies.[11]

The change in the fleet composition is also similar between the CAFE standards and feebate simulations. Under both policies, the percentage of microhybrids increases dramatically. Microhybrids are a technology that allows the vehicle to completely turn off the combustion engine when it would otherwise have idled, such as at a stoplight. Air conditioning, electronics, and radio would all be powered by a small battery, which would also be used to quickly re-start the engine. This technology can improve fuel economy by five to ten percent. At the same time, microhybrid vehicles are less expensive than full hybrids and much less expensive than dedicated electric vehicles, since the battery needed is much smaller and the technology more similar to today's conventional vehicles. By the end of 2011, there were already around five million microhybrids on the road worldwide, with most in Europe (Forbes 2012). Based on the relatively low cost of adding the microhybrid technology, the light duty fleet model in NEMS-NEPI indicates that nearly half of conventional gasoline vehicles sold in 2025 will be microhybrids in the CAFE simulation, with slightly less than this in the feebate scenario. A similar effect is found for diesel vehicles.

Interestingly, neither the CAFE standards nor feebate simulation results show a widespread adoption of either hybrid electric vehicles (i.e., electric-gasoline hybrids), such as the Toyota Prius, or dedicated battery electric vehicles. This result is due to the coefficients in the nested logit vehicle choice model, which may be conservative because they were estimated prior to the introduction of new hybrid models in recent model years. However, it is also possible that the market for new hybrids and electric vehicles will remain small, especially if lower-cost microhybrid technology begins to increase the fuel economy of a high percentage of the conventional gasoline vehicles offered, providing a slightly lower fuel economy choice for consumers at a much lower cost. While there is no way to verify the coefficients and the modelers' judgment that went into them, we can note that even if there are more hybrid electric vehicles on the market, most of the primary results would not appreciably change. In fact, the primary change would be a higher new vehicle price (and accordingly, cost of the policy).

[11] This result stems largely from the fact that most of the vehicles in the stock have the same fuel economy and thus would have the same driving. Only new vehicles entering the fleet would display a rebound effect. From this author's own calculations, it appears that the latest version of NEMS-NEPI includes a rebound effect of -0.1 (i.e., a 10 percent rebound) for new vehicles with improved fuel economy entering the fleet. This estimate is within the range of estimates in the literature, as discussed above.

While relatively small, one difference between the CAFE standard and the feebate policy relates to microhybrids, hybrid electric vehicles, and dedicated electric vehicles. Specifically, the feebate policy has relatively more hybrid electric vehicles and dedicated electric vehicles produced and relatively fewer microhybrids produced than the CAFE standard. Another difference relates to new vehicle sales. The modeled feebate appears to lead to slightly greater sales of new vehicles than either the baseline or the CAFE standard. This in turn implies slightly higher VMT (a slightly larger rebound effect). These differences may stem from how CAFE standards and feebates are modeled in NEMS-NEPI.

Under CAFE standards, there is a negative CAFE penalty for not meeting the standard, but no bonus for high fuel economy vehicles, as is the case under a feebate. Thus, the cost of hybrid/dedicated electric vehicles is lower in NEMS-NEPI under a feebate than under CAFE standards – leading to more hybrid and dedicated electric vehicles. However, these vehicles are more expensive than conventional vehicles, so this difference translates into differences in vehicle prices: new vehicles are more expensive on average under the feebate, especially for light trucks. When viewed in context with the economic theory, it is clear that a profit-maximizing automaker would adjust the price of high fuel economy vehicles (such as hybrid and dedicated battery electric vehicles) to find the most cost-effective way to meet the CAFE standards. So in reality, we would expect the production of microhybrids and hybrid electric vehicles under the two policies would be comparable. However, this difference in quite small.

The best way to implement a feebate policy in NEMS-NEPI is by changing both how automakers value technologies and the prices consumers see in the vehicle choice decision.[12] In contrast, CAFE standards are modeled entirely on manufacturers who add technology to meet the CAFE standards, which then leads to higher prices for consumers. Thus, CAFE standards increase the prices due to regulation, rather than an adjustment in consumer choice. The NEMS macroeconomic model treats price increases due to regulation slightly differently than due to consumer choice, thus leading to the difference in vehicle sales.[13] This asymmetric treatment of vehicle price increases is almost certainly an artifact of the model, but it does affect the social welfare results in the next section.

Finally, both CAFE standards and feebate runs show a shift from light trucks to cars relative to the reference case. This finding makes sense for a single pivot point feebate policy, for light trucks have lower fuel economy. Following the theory, this result no longer holds with multiple pivot points.[14] For CAFE standards, these results again make sense if there is a single CAFE standard. The CAFE standard simulation in AEO 2012 is a footprint based standard, but NEMS-

[12] If only the prices to consumers are changed in the nested logit, manufacturers in NEMS-NEPI would not correspondingly change the characteristics of the vehicles produced. Thus to model a feebate in NEMS-NEPI it is necessary to make changes to both the manufacturer decisions and consumer decisisons.
[13] I thank Frances Wood of OnLocation for this insight.
[14] The results with multiple pivot points are available from the author upon request.

NEPI does not model the automaker's incentive to increase the footprint of the vehicles in its fleet. Thus, I would not expect the shift from light trucks to cars to hold in reality. Yet despite these limitations, the NEMS-NEPI model provides a variety of impressively realistic results on all of the major policy outcomes of interest.

4.3 Social Welfare Effects

The above results quantify the similarities between CAFE standards and feebates in terms of primary outcomes. For policy, we also need to know the costs and benefits of each of the two policies to determine the social welfare consequences of the two policies. The welfare consequences can be divided into the effects on the automakers and the effects on consumers. NEMS-NEPI assumes that automakers price based on the production cost – a perfectly competitive market. Under this assumption, the policies do not affect the profits of the automakers at all.[15] Thus, this section will focus entirely on consumers.

The welfare consequences to consumers most directly depend on several factors: the fuel savings, the extra cost of the vehicles, the loss of other attributes that consumers may value, and the added welfare from the rebound effect. The fuel savings and extra cost of the vehicle are two quantities that can be derived from the results of the NEMS-NEPI model. However, NEMS-NEPI assumes that fuel economy is always improved by adding technologies to new vehicles, rather than trading off fuel economy for other valued attributes (e.g., horsepower, acceleration). This assumes away any loss in welfare due to automakers offering vehicles with fewer valued attributes to gain the greater fuel economy. Given this assumption, it is not possible to truly quantify these costs.[16] The added welfare from the rebound effect is likely to be quite small, for the driving is marginal driving that would not have been done without the higher fuel economy, so it is safely ignored in this analysis.

As described in Section 3, the true welfare effect to consumers depends importantly on whether consumers undervalue fuel economy. Moreover, it also depends on whether such an undervaluation implies that consumers are ex post better off if they were induced to purchase a higher fuel economy vehicle. The significance of undervaluation applies equally to CAFE standards and feebates. Given the state of the literature on this topic (e.g., see Helfand and Wolverton (2011), Anderson et al. (2011), and Gillingham and Palmer (2013)), it is impossible to calculate the welfare effects of CAFE without making a particular assumption about this topic. This is further complicated in the case of NEMS-NEPI because undervaluation is built into the

[15] Other common models of the nature of competition in the automobile market, such as differentiated products Bertrand oligopoly, would yield a different result. For example, see Jacobsen (2012).
[16] Small (2010) suggests that such "hidden amenity costs" are another possible explanation for myopia/undervaluation of fuel economy and offers several speculative approaches to calculate what can be thought of as an upper bound for these costs based on this explanation holding true. Given the nature of the literature in this area, I felt uncomfortable making a similar assumption.

light duty fleet model, so it would be inconsistent with the model to adopt the standard economic assumption that consumers consider future fuel savings the same way they do everything else.

Besides the direct effects, the policies may have other effects on consumers as well. There may be some change in tax revenue. However, as long as the government does not "waste" the tax revenue, any gain to vehicle purchasers is a loss to the government that must be made up elsewhere and vice versa. Thus changes in tax revenue can be thought of as a wash in terms of overall social welfare and should not be included in the calculation.[17] But, there may also be changes to the external costs of pollution, congestion, and accidents. These external costs have been well documented in the literature (Parry and Small 2005).

Taken on a whole, this discussion emphasizes that any welfare calculations must be appropriately interpreted. The three terms that can be reasonably well characterized are the fuel savings, the extra cost of the vehicles, and the external costs. To calculate these I follow the methodology carefully developed in Small (2010), which is based on linearizing the demand curve. This approach adopts the assumptions in NEMS-NEPI by assuming consumer undervaluation of future fuel savings in the vehicle purchase decision. I refer the interested reader to Small (2010) for details on the approach.[18] I adopt the same values for external costs as Small, which are originally based on Parry and Small (2005). When converted to 2010 dollars, these amount to \$0.048, \$0.040, \$0.027 for congestion, accident, and pollution external costs respectively in 2010, growing at 1.1 percent annually thereafter. Table 3 contains the results of the welfare calculations.

Table 3. Welfare calculations for CAFE standards and feebate

	2017-2025 CAFE standards			2017-2025 Feebate		
	2020	2025	2035	2020	2025	2035
Costs of policy (billion 2010$)						
Higher cost of vehicles/technology	9.26	35.44	33.21	8.97	37.54	31.14
Fuel cost savings	-9.73	-37.96	-39.85	-7.70	-37.87	-41.63
External costs from rebound	0.04	14.89	105.41	1.94	22.01	147.92
Total Policy Costs	-0.42	12.37	98.77	3.22	21.67	137.46
Policy effectiveness (reductions)						
Crude Oil consumption (mil bbl/yr)	31.0	155.8	323.5	22.32	136.42	322.8
Energy-related emissions (mil t CO_2)	14.2	80.7	186.0	11.98	61.4	163.9
Cost-effectiveness (policy cost per)						
Barrel of oil reduced (\$/bbl)	-13.6	79.4	305.3	144.24	158.9	425.9
Metric ton of CO2-e reduced (\$/t)	-29.7	153.3	531.0	268.83	352.7	838.8

[17] This deserves a caveat: if there is lost revenue that has to be raised by another means that is more highly distorting, there may be an additional deadweight loss that should be accounted for. However, this can also go in the other direction, so it is reasonable to ignore this effect.

[18] The three differences between these calculations and those in Small (2010) are that reduced tax revenues are not calculated (for those are a transfer), the discount rate for consumer decisions is set at 18%, and the social discount rate is set at 5%.

Notes: positive numbers are costs and negative numbers are benefits. The 2035 results assume a continuation of the 2017-2025 policy, with no further tightening after 2025. These are included for comparability with other concurrent NEPI studies.

The welfare calculation results follow logically from the results in Table 2. Since the feebate leads to more vehicle sales, the rebound effect is greater for the feebate than the CAFE standards policy. For example, the increase in VMT from the baseline under the feebate policy is 1.71 billion miles in 2020, while under CAFE standards it is 0.04 billion miles. With more driving, the external costs are greater under the feebate. This feature of the way feebates and CAFE standards are modeled tends to dominate the result and, as described before, is unlikely to hold in the real world.

The cost-effectiveness estimates suggest that the CAFE standards policy will have a cost of -$13.6 per barrel of oil reduced and -$29.7 per tonne of carbon dioxide equivalent reduced in 2020. Thus, for 2020 there are actually positive benefits from the policy even before accounting for the environmental benefits. These benefits are largely due to the future fuel savings and the assumption of undervaluation of such future fuel savings. The costs increase (i.e., benefits decrease) over time as the rebound effect begins to play a larger role. Corresponding to the high policy costs, the feebate policy appears to be much less cost-effective. However, if both CAFE standards and feebates had the same rebound effect, then we would expect the welfare implications to be very similar.

Rather than looking at individual years, it may also be useful to examine the cumulative present discounted value (PDV) of costs. Table 4 shows the PDV of the policy costs from 2010 through 2035 for three possible discount rate values: 5%, 10%, and 18%. The 5% discount rate perhaps best represents the social discount rate. 18% represents the discount rate some consumers may use for the purchase of durable goods and 10% is an intermediate value.

Table 4. 2010-2035 cumulative PDV welfare calculations for CAFE standards and Feebate

	2017-2025 CAFE standards			2017-2025 Feebate		
Discount Rate	5%	10%	18%	5%	10%	18%
Costs of policy (billion 2010$)						
Higher cost of vehicles/technology	195.5	86.2	27.2	199.3	87.8	27.6
Fuel cost savings	-219.9	-95.6	-29.5	216.4	-92.6	-27.8
External costs from rebound	220.0	80.0	18.1	327.6	121.3	28.6
Total Policy Costs	195.7	70.59	15.75	310.5	116.4	28.3

The results in Table 4 indicate that with the 5% social discount rate, the 2010-2035 PDV policy costs for CAFE standards are $195.7 billion, while those for the feebate policy are $310.5 billion. This difference again primarily reflects the differences in the external costs from the rebound effect.

Of course, this welfare analysis is by necessity incomplete for the reasons given above. Some of these factors would in fact tend to further raise the costs. But perhaps even more importantly, the degree to which consumers undervalue fuel economy is a wild card that can change the welfare analysis considerably (e.g., see the analysis in Parry et al. (2010)). Yet, this exercise is still illuminating in that it highlights the key factors that determine the welfare implications of these policies in the context of a realistic model of the light duty fleet and U.S. energy system.

5. Conclusions

The light duty vehicle fleet has long been the focus of policies aiming to reduce oil imports and help clear our air. The keystone policy in the United States continues to be CAFE standards, but increasingly feebates are making their way into the policy discussion. This paper clarifies the incentives provided by both CAFE standards and feebates, showing how a feebate can be designed to provide nearly identical incentives to CAFE standards. Indeed, a feebate policy can be designed to be equivalent to any CAFE standards policy with simple straightforward formula. The intuition for this equivalence is analogous to the intuition for why a cap-and-trade system can provide the same incentives as a tax – the decision to be discouraged is priced on the market.[19]

However, the exact design details of the feebate or CAFE standards policy are critical for the welfare implications of the policies. The recent changes to CAFE standards that provide for tradable CAFE credits and banking/borrowing of CAFE credits have made CAFE standards much more of a market-based policy, and more similar to a classic feebate than the previous CAFE standards. Automakers now have much more compliance flexibility than they had previously, which echoes the flexibility provided under a feebate. Similarly, with CAFE trading automakers will have continual incentives to improve fuel economy, just as they would under a feebate.

However, the analytical results also highlight that the changes have not been entirely economic efficiency-improving. By switching to a footprint-based regulation, the current CAFE standards lead to a perverse incentive: automakers will have an incentive to upsize their vehicles. The prior CAFE standards provided the same incentive by providing a separate standard for passenger cars and light trucks, but with a footprint-based standard, this incentive is likely to be more pronounced. Of course, the analysis also shows that a footprint-based feebate could also be designed, with the same inherent issue. This may be the likely outcome of the political process, for an footprint-based policy is appealing to domestic automakers with heavier and larger vehicles than their foreign counterparts. These distributional consequences aside, it is clear that

[19] Just as for a cap-and-trade and a tax, uncertainty may change the optimal choice between the two policy instruments. This is an interesting area for future work.

a feebate with a single pivot point or a CAFE standard with a single fleet would be preferred on the grounds of economic efficiency.

The NEMS-NEPI results provide quantitative estimates of how a feebate policy could be designed to closely match a CAFE policy. With a feebate designed to closely match CAFE standards, either policy could improve fuel economy by 30 percent by 2025 relative to the reference case. While NEMS-NEPI has some limitations, which affect the interpretation of some of the results, central case estimates (including undervaluation of future fuel savings) indicate that the currently proposed CAFE standards have a *negative* welfare cost per tonne of CO_2-equivalent in early years (similar to the rulemaking technical support documentation), for the future fuel savings outweigh the policy costs. In PDV terms, there would be a modest total policy cost under a 5% social discount rate. Based on the analytical results, I argue that the policy costs for feebates should be similar to those for CAFE standards. The welfare calculations for the NEMS-NEPI feebate indicate the importance of a greater rebound effect. This leads lower cost-effectiveness. Since this modeling feature does not follow from economic theory, the CAFE standards policy welfare estimate is perhaps a better one to use.

The findings in this study underscore the importance of the details of the regulation for its efficiency and cost-effectiveness. Are there reasons to more generally prefer a feebate over CAFE standards? While the answer depends on the particular policy implemented, feebates provide several advantages. By implementing a feebate, there may be the possibility to introducing a transparent policy that more clearly allows the market to work to promote higher fuel economy vehicles. A new feebate policy could even be layered on top of the current CAFE standards, for with a sufficiently high feebate, the CAFE standards would not be binding. With a feebate, it may be more difficult to add details to the policy that reduce its cost-effectiveness. On the other hand, the distributional issues across automakers may deliver the same pressures that led to features such as footprint-based standards and alternative fuel credits in CAFE standards.

Feebates are also advantageous when there are complementary policies, such as state-level rebates for hybrid vehicles. With a feebate, the additional rebates for hybrid vehicles would be additive to the feebate and would affect the market. With CAFE standards, such policies would simply allow the automakers to adjust their prices to sell more high-profit low fuel economy vehicles, since they would have more room under the standard by the additional hybrid sales (Gillingham 2011; Roth 2012). This difference between CAFE standards and feebats is equally important under footprint-based standards as long as there is credit trading across footprint classes and across fleets.

A third advantage of a simple feebate is that the administrative costs may be somewhat lower. Setting CAFE standards, and especially a complicated footprint-based standard, is not a simple administrative task. To implement such a policy requires detailed modeling of not only the market, but also the technologies available to each of the automakers. Moreover, automakers have to bear administrative costs in trading CAFE permits. A feebate with a single pivot point would be relatively easy to implement, and would have even lower administrative costs if the point of regulation is at the manufacturer level. With multiple pivot points, such as with a footprint-based feebate, the government administrative costs would likely be the same as the equivalent CAFE standards policy. But, it would still be lower for the automakers, for there would be no need to trade any permits.

This exploration into feebates does not lead to a conclusive result about whether feebates or CAFE standards are preferred when more direct policies, such as fuel taxes, are off the table. With trading and banking/borrowing, the new CAFE standards can achieve a cost-effectiveness close to feebates. Feebates are thus only somewhat preferable, due to regulatory transparency, complementary policies, and administrative costs. Future work extending the analytical results to uncertainty and exploring some of behavioral economics issues relating to salience and undervaluation of fuel economy in vehicle choice hold great promise to further clarify the choice between CAFE standards and feebates.

Appendix

Proof of Proposition 1. Consider the first of the three first order conditions for feebates and plug in a linear feebate and rearrange:

$$\sum_{j\in J}[p_j \frac{\partial q_j}{\partial p_i} + q_j + R_k \left(\frac{1}{MPG_{0k}} - \frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial p_i}] = \sum_{j\in J} \frac{\partial C_j}{\partial q_i}\frac{\partial q_j}{\partial p_i}.$$

This can be rewritten as

$$\sum_{j\in J}[p_j \frac{\partial q_j}{\partial p_i} + q_j] + \sum_k \sum_{j\in J_k} R_k \left(\frac{1}{MPG_{0k}} - \frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial p_i} = \sum_{j\in J} \frac{\partial C_j}{\partial q_i}\frac{\partial q_j}{\partial p_i}.$$

This equation is identical to the first of the first order conditions for CAFE standards if there exist R_k and MPG_{0k} such that for each j

$$R_k \left(\frac{1}{MPG_{0k}} - \frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial p_i} = \lambda_k \left(1 - \frac{\sigma_k}{MPG_j}\right)\frac{\partial q_j}{\partial p_i}.$$

Solving, we find $\lambda_k = R_k/MPG_{0k}$ and $R_k = \lambda_k\sigma_k$, and accordingly, $MPG_{0k} = \sigma_k$.

The second first order condition for a linear feebate can be written as:

$$\sum_{j\in J}[p_j \frac{\partial q_j}{\partial \theta_i} + R_k \left(\frac{1}{MPG_{0k}} - \frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial \theta_i}] = \sum_{j\in J} \frac{\partial C_j}{\partial \theta_i} + R_i' \quad \forall\, \theta_i \neq MPG_i$$

This equation is identical to the second of the first order conditions for CAFE standards if there exist R_k and MPG_{0k} such that for each j

$$R_k \left(\frac{1}{MPG_{0k}} - \frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial \theta_i} = \lambda_k \left(1 - \frac{\sigma_k}{MPG_j}\right)\frac{\partial q_j}{\partial \theta_i}.$$

Solving again yields $R_k = \lambda_k\sigma_k$ and $MPG_{0k} = \sigma_k$

The third first order condition for a linear feebate can be written as:

$$\sum_{j\in J}(p_j \frac{\partial q_j}{\partial MPG_i} + R_k \left(\frac{1}{MPG_{0k}} - \frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial MPG_i} + \frac{\partial F_j}{\partial MPG_i} q_j) = \sum_{j\in J} \frac{\partial C_j}{\partial MPG_i} + R_i'.$$

Plugging in the first derivative of the feebate and rearranging, we have

$$\sum_{j\in J} p_j \frac{\partial q_j}{\partial MPG_i} + \sum_k \sum_{j\in J_k} R_k \left(\frac{1}{MPG_{0k}} - \frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial MPG_i} + \frac{R_k}{MPG_i^2} q_i = \sum_{j\in J} \frac{\partial C_j}{\partial MPG_i} + R_i'.$$

This equation is identical to the third of the first order conditions for CAFE standards there exist R_k and MPG_{0k} such that for each j

$$R_k\left(\frac{1}{MPG_{0k}}-\frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial MPG_i}+\frac{R_k}{MPG_i^2}q_i=\lambda_k[\left(1-\frac{\sigma_k}{MPG_j}\right)\frac{\partial q_j}{\partial MPG_i}+\frac{\sigma_k}{MPG_i^2}q_i]$$

Solving this yields $R_k = \lambda_k\sigma_k$ and $MPG_{0k} = \sigma_k$. Thus, there exists a linear feebate that is exactly equivalent to a CAFE standard, with the pivot points given by σ_k and rates given by $\lambda_k\sigma_k$. Q.E.D.

Proof of Proposition 2. Recall that for all attributes of the vehicle besides fuel economy, the automaker's first order condition for profit maximization is:

$$\sum_{j\in J} p_j\frac{\partial q_j}{\partial \theta_i}+\sum_k \lambda_k\sum_{j\in J_k}\frac{\partial q_j}{\partial \theta_i}\left(1-\frac{\sigma_k}{MPG_j}\right)=\sum_{j\in J}\frac{\partial C_j}{\partial \theta_i}+R_i' \quad \forall\, \theta_i \neq MPG_i.$$

Under a footprint-based CAFE standard, there is a new term in the automaker's first order condition with respect to the footprint attribute:

$$\sum_{j\in J} p_j\frac{\partial q_j}{\partial FP_i}+\sum_k \lambda_k\sum_{j\in J_k}\frac{\partial q_j}{\partial FP_i}\left(1-\frac{\sigma_k}{MPG_j}\right)-\frac{\lambda_k q_i}{MPG_i}\frac{\partial \sigma_k}{\partial FP_i}=\sum_{j\in J}\frac{\partial C_j}{\partial FP_i}+R_i'.$$

Note that all of the other first-order conditions remain identical to the standard CAFE case. Since, by definition, an increase in the footprint strictly decreases the standard, $\frac{\partial \sigma_k}{\partial FP_i} < 0$ and thus the additional term is negative. This implies that the marginal benefit of increasing the footprint is greater than without this term, while the marginal cost remains the same. Thus, a profit maximizing manufacturer will choose a larger footprint for vehicle *i*. Q.E.D.

Proof of Proposition 3. Without loss of generality, I assume that the pivot point changes continuously with the footprint. Discrete changes associated with footprint categories are an easy generalization, but provide a less intuitive proof. Under a linear feebate with pivot points at every footprint, there is again a new term in the automaker's first order condition with respect to footprint:

$$\sum_{j\in J}[p_j\frac{\partial q_j}{\partial FP_i}+R_k\left(\frac{1}{MPG_{0k}}-\frac{1}{MPG_j}\right)\frac{\partial q_j}{\partial FP_i}-\frac{R_k q_i}{MPG_{0k}^2}\frac{\partial MPG_{0k}}{\partial FP_i}]=\sum_{j\in J}\frac{\partial C_j}{\partial FP_i}+R_i'.$$

Besides this first-order condition, all of the other first order conditions are identical to the standard feebate. As long as a larger footprint means a lower standard, $\frac{\partial MPG_{0k}}{\partial FP_i} < 0$. So the new term in the first order condition is negative. Thus a profit maximizing manufacturer will choose a larger footprint for vehicle *i*. Q.E.D.

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About the Contributor

Kenneth Gillingham is an Assistant Professor of Economics at Yale University, with a primary affiliation at the Yale School of Forestry & Environmental Studies and a secondary affiliation with the Yale Economics Department. Professor Gillingham's research focuses on energy efficiency, the adoption of new energy technologies, and transportation. He has published widely in academic journals on topics such as the energy efficiency gap, the consumer response to different transportation policies, and the economic efficiency of environmental policies. Professor Gillingham was a Fulbright recipient to New Zealand, where he researched New Zealand's solar energy policies. He has previously worked at the White House Council of Economic Advisers, Resources for the Future, and the Pacific Northwest National Laboratory. His Ph.D. is in Management Science & Engineering with a minor in Economics from Stanford University. He also holds an M.S. in Statistics and an M.S. in Management Science & Engineering from Stanford University, as well as an A.B. from Dartmouth College in Economics and Environmental Studies.