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Using Loopholes to Reveal the Marginal Cost of Regulation: The Case of Fuel-Economy Standards

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Estimating the cost of regulation is difficult. Firms sometimes reveal costs indirectly, however, when they exploit loopholes to avoid regulation. We apply this insight to fuel economy standards for automobiles. These standards feature a loophole that gives automakers a bonus when they equip a vehicle with flexible-fuel capacity. Profit-maximizing automakers will equate the marginal cost of compliance using the loophole, which is observable, with the unobservable costs of strategies that genuinely improve fuel economy. Based on this insight, we estimate that tightening standards by one mile per gallon would have cost automakers just $9–$27 per vehicle in recent years. (*JEL* L51, L62, Q48)

Estimating the cost of regulation is difficult. Few regulations allow trading that could reveal compliance costs through transaction prices, and regulated firms rarely have an incentive to report costs truthfully. Some regulations, however, feature "loopholes" that allow firms to relax regulatory constraints. When the cost of using a loophole is known, researchers can infer the marginal cost of regulation indirectly for firms that exploit the loophole. We demonstrate that firms in the auto industry reveal the marginal cost of complying with fuel-economy standards when they exploit a loophole that overstates the efficiency of "flexible-fuel" vehicles. Using this approach, we estimate that tightening fuel-economy standards by one mile per gallon in recent years would have cost domestic automakers between $9 and $27 in profit per vehicle. Our estimates contrast with conventional wisdom, which holds that compliance costs are very high, and our estimates are far lower than other recent attempts to measure these costs directly (Jacob Gramlich 2010; Mark R. Jacobsen 2010). Unlike these other estimates, our costs are well below the noncompliance penalty of $55, which should act as a plausible upper bound on costs. More generally,

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the loophole methodology we develop here may help reveal marginal compliance costs for other regulations whose costs are otherwise difficult to gauge.

Corporate Average Fuel Economy (CAFE) standards require automakers to achieve a minimum average mileage across their entire vehicle fleet. Firms whose fleet average falls below the minimum are subject to a fine. CAFE is the most important policy affecting fuel economy in the United States, and an extensive economics literature studies its effects.[1] A key unknown parameter in this literature is the shadow price on the CAFE standard, which Goldberg (1998) takes to equal the $55 fine for noncompliant firms, and zero otherwise. The shadow price quantifies the firm's marginal cost of complying with CAFE in equilibrium and is therefore critical for understanding both the cost of the regulation and for simulating the effects of policy changes. Other studies adopt the $55 penalty as a measure of marginal compliance costs for all constrained firms, even though domestic automakers do not pay fines (Jonathon Rubin and Paul Leiby 2000; Yimin Liu and Gloria E. Helfand 2009). Our cost estimates fall between zero and $55.

The Alternative Motor Fuels Act (AMFA) modified CAFE regulations starting in 1993 by crediting vehicles capable of burning both gasoline and ethanol—flexible-fuel vehicles—with about two-thirds better mileage than they actually achieve.[2] Automakers can make any conventional vehicle a flexible-fuel vehicle through a minor modification, which adds only $100–$200 in production cost, as we discuss in detail below. As long as consumers fill their tanks with gasoline instead of ethanol, a flexible-fuel vehicle is identical to its gasoline-only counterpart. Thus, automakers can improve their average mileage under CAFE regulations by fitting existing models with flexible-fuel capacity, even though this has no impact on actual mileage. Adding flexible-fuel capacity is therefore a substitute for other compliance strategies, such as modifying vehicles to be more efficient or selling a larger fraction of small vehicles. The basic insight of this paper is that a profit-maximizing firm will equate the marginal costs of different compliance strategies. Thus, we can use the cost of exploiting the flexible-fuel loophole, which is readily observable, to estimate the cost of other compliance strategies, whose costs are otherwise hidden.

Our methodology provides estimates for the shadow price of CAFE during recent years when automakers were producing flexible-fuel vehicles. Our results indicate that, in recent years, compliance costs have been quite low. Our methodology does not yield estimates of compliance costs for earlier years when the flexible-fuel loophole did not exist, nor does it predict how compliance costs might respond to future policy changes, shifts in demand due to higher or lower gasoline prices, new vehicle attributes and technologies, or changes in market structure, since we take all of these factors as given. As such, we consider our approach a complement to traditional structural methods that yield clearer out-of-sample predictions. Since our parameter has a precise interpretation derived from a profit-maximizing model, our results could be used to calibrate a structural model of the industry during our study period.

[1] The seminal paper in this literature is Pinelopi Koujianou Goldberg (1998), which estimates effects on new vehicle prices, sales volumes, and fuel consumption, comparing CAFE's welfare cost to that of a gasoline tax. Other recent examples include Andrew N. Kleit (2004), David Austin and Terry Dinan (2005), and Sarah E. West and Roberton C. Williams III (2005).

[2] Flexible-fuel vehicles can run on a fuel blend known as "E85," which contains 85 percent pure ethanol and 15 percent gasoline. We refer to this fuel as "ethanol" throughout.

More importantly, our results, which have greater transparency, can be used to test the validity of parameter estimates from a structural model, giving greater credence to the model's predictions when the parameters coincide. Unfortunately, in this case, our loophole estimates appear to cast doubt on other recent results, rather than provide affirmation.

We begin by modeling the profit-maximization decision of an oligopolistic automaker. The automaker faces a fuel-economy constraint but can relax the constraint, up to a point, by producing flexible-fuel vehicles. The model provides four sufficient conditions under which we can infer the marginal cost of tightening the CAFE standard using our methodology. Under these conditions, the automaker will equate the marginal cost of improving mileage using the flexible-fuel loophole with the marginal cost of improving mileage through other means.

The empirical portion of the paper demonstrates that these four sufficient conditions hold for domestic automakers in recent years. Using administrative data from the Department of Transportation, we first show (i) that domestic automakers were constrained by CAFE standards and used flexible-fuel vehicles to comply. They rarely added flexible-fuel capacity to more than one type of vehicle, and unconstrained Asian firms did not produce any flexible-fuel vehicles. We then show (ii) that domestic automakers installed flexible-fuel capacity on some but not all units for relevant models, and (iii) that they rarely exceeded the maximum gain in fuel economy permitted under the flexible-fuel provision.

Finally, using transaction data to analyze both prices and quantities, we show (iv) that marginal consumers do not value flexible-fuel capacity. Automakers sell a large portion of their flexible-fuel vehicles to consumers living in states with virtually no ethanol fueling stations. Consumers in these states almost certainly do not value flexible-fuel capacity, since they are not able to purchase ethanol. Furthermore, our analysis of transaction prices for flexible-fuel vehicles and comparable gasoline vehicles indicates that consumers do not pay more for flexible-fuel capacity. This is consistent with survey evidence that many car owners do not even know they own flexible-fuel vehicles.

Because our four sufficient conditions hold empirically, the flexible-fuel provision reveals the cost of marginally tighter CAFE standards. Compliance costs are a function of a flexible-fuel vehicle's actual mileage and incremental production cost, which reportedly ranges from \$100 to \$200. For automakers that produce flexible-fuel vehicles, this range implies that tightening the standard for light trucks by one mile per gallon in recent years would have cost firms \$10 to \$27 in lost profit per truck. Tightening the standard for passenger cars would have cost \$9 to \$18 per car. Because automakers equate the marginal costs of alternative compliance strategies, our cost estimates also reflect lower profit margins on smaller, more efficient vehicles, as well as the gap between incremental production costs and willingness to pay for fuel-saving modifications. These estimates are substantially lower than other recent estimates based on structural methodologies. Below, we offer several reasons why we find our results more plausible.

More broadly, our approach suggests that researchers should consider loopholes when trying to estimate compliance costs for other regulations. A prominent example is "incentive zoning." Under incentive zoning, cities relax zoning constraints on height and density if developers provide open space, affordable housing, or other public goods.[3] Following our methodology, researchers could estimate the marginal benefit to developers of easing zoning restrictions by quantifying how much developers spend to avoid these restrictions. Similarly, many environmental regulations block new development in wetlands, the habitats of specific animals, or other sensitive ecosystems. Regulators often relax these constraints in exchange for developers purchasing and preserving similar land elsewhere. Other examples include carpool lanes, which commuters can access by matching with other commuters or by purchasing a hybrid vehicle in some US states; ambient air quality standards, which firms can meet by reducing their own emissions or by purchasing and shutting down other polluters; and carbon emissions targets under the Kyoto Protocol, which industry can achieve by cutting emissions or by purchasing offsets through a Clean Development Mechanism. We suspect that researchers could identify costly loopholes in numerous other regulations. In many cases, the cost of exploiting the loophole will equal the marginal cost of other, conventional compliance strategies.

Our analysis of the market for flexible-fuel vehicles also contributes to the policy debate on alternative fuels. The original rationale for the flexible-fuel provision was to induce automakers to make flexible-fuel vehicles in the hope that ethanol fueling infrastructure would follow. In reality, ethanol infrastructure has not kept pace with flexible-fuel production, and few vehicles ever run on ethanol.[4] Theory therefore suggests that AMFA increases gasoline consumption and greenhouse gas emissions by weakening CAFE standards (Liu and Helfand 2009), and a consensus has emerged that the flexible-fuel provision has not achieved its goals (National Academy of Sciences 2002). Our empirical analysis, which shows that automakers allocate most flexible-fuel vehicles to locations that lack ethanol, is consistent with this conclusion. Current law extends the flexible-fuel loophole to 2014, at which point it is phased out between 2015 and 2019. Thus, for the next decade, this loophole will remain an important part of CAFE regulations.

The remainder of this paper is organized as follows. Section I models an automaker's decision to use the flexible-fuel loophole to relax fuel-economy constraints and establishes sufficient conditions under which we can infer marginal compliance costs. The next several sections demonstrate that these conditions hold empirically in recent years. Section II shows that domestic automakers use flexible-fuel vehicles to comply with CAFE standards, that they install flexible-fuel capacity on some but not all units, and that they rarely exhaust the flexible-fuel loophole. Section II also shows that the set of vehicles we observe with flexible-fuel capacity is broadly consistent with our model's predictions. Section III argues that marginal consumers do not value flexible-fuel capacity. Section IV then uses publicly reported estimates for the incremental cost of producing a flexible-fuel vehicle to calculate the marginal cost of complying with fuel-economy standards. Section V briefly discusses what the results imply about the CAFE program's net social benefits during our study period, and section VI concludes.

[3] Incentive zoning began in Chicago and New York City, where developers were allowed to exceed height and density restrictions if they provided plaza space (Marc A. Weiss 1992; Marya Morris 2000). At least half of all cities and towns with zoning laws reportedly have some incentive zoning program (Morris 2000).

[4] Anderson (2011) shows that demand for ethanol exists and is sensitive to fuel prices. Since supply is scarce in all but a few locations, however, flexible-fuel owners generally do not have access to ethanol.

I. Revealing the Cost of Fuel-Economy Standards

We model an automaker as maximizing profits in an oligopolistic framework, subject to CAFE constraints. We require a fair bit of notation to portray the market structure and policy, but the bottom line is simple. An automaker faces a minimum mileage constraint, which it can relax by increasing the share of flexible-fuel vehicles. The first-order condition characterizing optimal flexible-fuel shares yields an equation that defines the shadow price on the CAFE constraint in terms of observable parameters.

Automakers can also boost their mileage by cutting prices on smaller, more efficient cars, or by modifying particular models to be more efficient. The first-order conditions for these strategies involve demand elasticities and markups, which are specific to the structure of the pricing equilibrium, and which depend on the cost of fuel-saving modifications. Thus, to estimate the shadow price of CAFE using these conditions, a researcher must estimate a large number of demand and production cost parameters and must take a stand on the nature of the market equilibrium.

In contrast, our loophole methodology allows us to estimate the shadow price on the constraint while remaining agnostic about the details of the oligopolistic equilibrium and key parameters that we do not observe. Importantly, at an interior solution, the shadow price we estimate based on the cost of exploiting the flexible-fuel loophole will equal the cost of compliance using other, conventional strategies.

A. *Market Structure*

We assume that an oligopolistic automaker complying with fuel-economy standards maximizes profits with respect to the prices, mileage, and flexible-fuel shares of the models it produces:

$$(1) \qquad \max_{\mathbf{m},\mathbf{p},\boldsymbol{\theta}} = \sum_{j\in\mathcal{M}} \big(p_j - c_j(m_j) - \alpha_j\theta_j\big)q_j(\mathbf{p},\mathbf{m}) - \sum_{j\in\mathcal{M}} I(\theta_j > 0) \cdot F_j,$$

where $\mathcal{M}$ is the set of models the automaker produces; p_j is the price the automaker charges for model j; m_j is the model's fuel economy in miles per gallon; q_j is its sales quantity, which we assume is continuous in prices $\mathbf{p}$ and mileage $\mathbf{m}$ for all models of all producers; c_j is the constant marginal cost of the gasoline-only version of the model, which we assume is continuous and increasing in mileage; $\theta_j \in [0,1]$ is the model's flexible-fuel share, or the fraction of units with flexible-fuel capacity; α_j is the incremental production cost of outfitting one such unit with flexible-fuel capacity; and F_j is the sunk fixed cost of engineering the model to have flexible-fuel capacity, which the automaker pays if the model's flexible-fuel share exceeds zero, as denoted by the indicator function $I(\theta_j > 0)$. Profits equal the sum over all models of price minus average variable cost multiplied by quantity, minus engineering fixed costs. We assume that the set of models is fixed.

Fitting a vehicle with flexible-fuel capacity entails both variable and fixed costs. In addition to having larger fuel injectors, flexible-fuel vehicles have fuel-system components made from materials that are more resistant to the corrosive nature of ethanol. Earlier models also had special fuel sensors to detect how much ethanol was in the fuel. Incremental costs vary from model to model, depending on a model's engine technology. Often more important than the hardware changes themselves, however, is the engineering time and effort needed to add flexible-fuel capacity. Outfitting a new model with flexible-fuel capacity requires making minor design changes, modifying on-board software, doing additional engine calibration work, and performing extra emissions testing. These up-front fixed costs can be substantial.

In equation (1) we specify a separate fixed cost for each model. In reality, different models often share the same engines, implying substantial overlap in fixed costs. Thus, when we analyze actual flexible-fuel production below, we focus on flexible-fuel shares for specific engine sizes, which proxy for models with shared fixed costs.

Our model implicitly assumes that consumers do not care about flexible-fuel capacity one way or the other. Quantities do not depend on flexible-fuel shares, which implies, for example, that no consumer would switch from a Honda Accord to a Chevy Impala if General Motors increased the fraction of Impalas with flexible-fuel capacity. Likewise, we do not include separate prices for flexible-fuel vehicles and their gasoline-only counterparts. Since consumers in our model regard the vehicles as identical, no consumer would pay more or less for an Impala with flexible-fuel capacity, and the automaker sets a single price for all Impalas. In reality, some consumers surely prefer flexible-fuel vehicles, while other consumers may even have a distaste for such vehicles. This will not matter for our result so long as many marginal consumers are indifferent between flexible-fuel vehicles and comparable gasoline vehicles whose prices are equal. Later, we present empirical evidence supporting this claim.

B. *Fuel-Economy Standards*

Fuel-economy standards impose a constraint that sets a minimum average mileage for the automaker's fleet, taking into account the flexible-fuel vehicle loophole. The law also imposes a second, "backstop" constraint, which effectively limits the automaker's ability to boost its fuel-economy rating using flexible-fuel vehicles. The first constraint takes the following form:

$$\left(\sum_{j\in\mathcal{M}} \frac{q_j(\mathbf{p},\mathbf{m})}{Q} \cdot \frac{1 - \theta_j(1 - \beta)}{m_j}\right)^{-1} \geq \sigma, \tag{2}$$

where σ is the fuel-economy standard in miles per gallon, m_j is the mileage of model j; $\beta \in [0,1]$ is the incentive for flexible-fuel vehicles; $Q = \sum_{j\in\mathcal{M}} q_j(\mathbf{p},\mathbf{m})$ is the automaker's total sales volume; and all other parameters are as above. The constraint requires that an automaker's AMFA fuel economy—that is, the sales-weighted harmonic-average mileage of the automaker's vehicles, calculated using flexible-fuel incentives—exceed the CAFE standard of σ.

We can interpret β as the share of a flexible-fuel vehicle's fuel consumption that actually counts toward calculating average mileage, which means that the calculation ignores the remaining $1 - \beta$. Thus, the automaker can relax the CAFE constraint simply by increasing the share of flexible-fuel vehicles, that is, by choosing $\theta_j > 0$, without adjusting prices or making any other design changes. Current legislation fixes the flexible-fuel incentive at $\beta \approx 0.6$, giving automakers with binding constraints a strong implicit subsidy to produce flexible-fuel vehicles.[5] For a sense of how strong this incentive is, note that adding flexible-fuel capacity increases a vehicle's effective mileage by about $1/0.6 - 1 \approx 67$ percent, which amounts to treating a flexible-fuel Hummer like a Toyota Camry or a flexible-fuel Camry like a Toyota Prius. Increasing a model's flexible-fuel share increases average mileage because the standard treats flexible-fuel vehicles as though they achieve better mileage than they actually do.

The automaker is limited in its ability to improve fuel economy using the flexible-fuel loophole. This limit acts like a "backstop" on actual fuel economy by adding a second constraint:

$$(3)\quad \left(\sum_{j \in \mathcal{M}} \frac{q_j(\mathbf{p},\mathbf{m})}{Q} \cdot \frac{1 - \theta_j(1 - \beta)}{m_j}\right)^{-1} - \left(\sum_{j \in \mathcal{M}} \frac{q_j(\mathbf{p},\mathbf{m})}{Q} \cdot \frac{1}{m_j}\right)^{-1} \leq \phi,$$

where $\phi > 0$ is the maximum gain in average mileage permitted under the flexible-fuel loophole, and all other parameters are as above. This constraint requires that the automaker's AMFA fuel economy (the first term on the left-hand side) not exceed its actual fuel economy (the second term) by more than miles per gallon. Legislation fixes this limit at $\phi = 1.2$ miles per gallon.

C. *Choosing Optimal Flexible-Fuel Shares*

The automaker will simultaneously choose prices, mileage, and flexible-fuel shares for all vehicles. Here, we focus on the choice of flexible-fuel shares. We present only the first-order conditions with respect to these shares, but similar conditions exist for prices and mileage. We remain agnostic as to the competitive behavior automakers use to arrive at an equilibrium in vehicle prices, quantities, and mileage. We simply assume that some equilibrium mapping from prices and mileage to sales quantities exists, and that automakers choose flexible-fuel shares optimally given this mapping.

The Lagrangian for the automaker's maximization problem (conditional on the set of models chosen to have flexible-fuel capacity) is given by

$$(4)\quad \mathcal{L} = \sum_{j \in \mathcal{M}} (p_j - c_j - \alpha_j \theta_j) q_j + \lambda \cdot Q\left[\left(\sum_{j \in \mathcal{M}} \frac{q_j}{Q} \cdot \frac{1 - \theta_j(1 - \beta)}{m_j}\right)^{-1} - \sigma\right]$$

$$+ \mu \cdot Q\left[\phi - \left(\sum_{j \in \mathcal{M}} \frac{q_j}{Q} \cdot \frac{1 - \theta_j(1 - \beta)}{m_j}\right)^{-1} + \left(\sum_{j \in \mathcal{M}} \frac{q_j}{Q} \cdot \frac{1}{m_j}\right)^{-1}\right],$$

[5] In practice, $\beta = \rho r g + (1 - \rho)$, where $\rho \in [0, 1]$ is the assumed fraction of miles that the vehicle drives using E85 ethanol, $r > 1$ is the ratio of ethanol to gasoline fuel consumption per mile, and $g \in [0, 1]$ is the assumed gasoline content of E85. The credit's logic is that it purports to count only gasoline consumption when determining a vehicle's contribution toward average fuel economy. Current legislation fixes $\rho = 0.50$, which dramatically overstates the fraction of miles that flexible-fuel vehicles actually run on ethanol, and sets $g = 0.15$, which is the fraction gasoline content of E85. In practice, r varies slightly among flexible-fuel vehicles, averaging about 1.35, which implies that flexible-fuel vehicles achieve about 35 percent higher fuel economy on gasoline, or $1 - 1/1.35 = 25$ percent lower fuel economy on ethanol. We assume for simplicity that r is the same for all vehicles so that β is also the same for all vehicles.

where λ and μ are the shadow prices on the constraints, all other variables are as above, and we have suppressed the arguments of functions for convenience. Note that we have multiplied both constraints by Q, which allows us to interpret the shadow prices in dollars per mile per gallon per vehicle. Flexible-fuel shares are choice variables only for models on which the automaker has paid the fixed engineering costs; flexible-fuel shares are zero for other models. When the constraints are binding, the shadow prices implicitly tax inefficient models and subsidize efficient models. The shadow prices also quantify the marginal cost, in terms of lower profits, resulting from tighter fuel-economy standards. Equivalently, the shadow prices quantify the marginal benefit of looser standards.

Differentiating the Lagrangian with respect to the flexible-fuel share of model k leads to the following first-order condition:

$$(5) \qquad -\alpha_k + (\lambda - \mu)\frac{1 - \beta}{m_k}M^2 = 0,$$

where q_k factors out of both terms, and M is the automaker's AMFA mileage, which is given by the left-hand side in equation (2). This first-order condition holds with equality only for models whose flexible-fuel shares are strictly greater than zero and strictly less than one. At corner solutions the equality becomes an inequality. The first term is the incremental cost of adding flexible-fuel capacity to one unit. In the second term, $(1 - \beta)M^2/m_k$ is the (quantity weighted) gain in average mileage the automaker earns by adding flexible-fuel capacity to another unit, while the shadow prices convert this gain into dollars of marginal benefits. If the backstop constraint is slack, then this gain has value equal to the shadow price on the first constraint. If the backstop is binding, however, then the shadow price on the second constraint devalues this gain to the point that the automaker has no desire to pursue it. Thus, the automaker simply equates the incremental cost of adding flexible-fuel capacity to another unit with the marginal benefit in terms of relaxing the first constraint, net of any adverse impact on the second constraint.[6]

D. *Flexible-Fuel Loophole Reveals Marginal Compliance Costs*

When the second constraint is slack, the first-order conditions for flexible-fuel shares reveal the shadow price on the first constraint, which is the key insight of this paper. Rearranging equation (5) and setting $\mu = 0$ gives

$$(6) \qquad \lambda = \alpha_k \cdot \frac{m_k}{(1 - \beta)M^2},$$

[6] One might be concerned about the second-order conditions because mileage and flexible-fuel shares both enter nonlinearly in the constraint. Without a number of additional assumptions, it is impossible to verify the second-order conditions fully. We have, however, analyzed the single-vehicle model where firms choose both mileage and flexible-fuel shares, which requires only the additional assumption that variable profits are concave in mileage (i.e., that costs are convex in mileage) but still captures the nonlinearity in the constraint. In this case, the second-order condition holds, indicating that the first-order conditions indeed characterize the maximum. Details of our analysis are available upon request.

which holds with equality for any model at an interior flexible-fuel share. The shadow price λ on the first constraint equals the incremental cost of adding flexible-fuel capacity divided by the corresponding gain in sales-weighted AMFA fuel economy that flexible-fuel capacity affords.

This shadow price is also related to the cost of CAFE standards. Differentiating the automaker's Lagrangian in equation (4) at the optimum with respect to the nominal fuel-economy standard and then dividing by total sales quantity gives marginal compliance costs in terms of lost profit per vehicle:[7]

$$\frac{\partial \mathcal{L}^*}{\partial \sigma}\frac{1}{Q} = -\lambda. \tag{7}$$

Substituting for the shadow price using equation (6) yields marginal compliance costs per vehicle as a function of known parameters:

$$\frac{\partial \mathcal{L}^*}{\partial \sigma}\frac{1}{Q} = -\frac{\alpha_k \cdot m_k}{(1-\beta)M^2}. \tag{8}$$

Marginal compliance costs are a simple function of the incremental cost of adding flexible-fuel capacity to models at interior flexible-fuel shares, the mileage of these models, the flexible-fuel credit, and average AMFA mileage. At the optimum, the automaker will equate the marginal cost of relaxing the constraint using the flexible-fuel loophole with the marginal cost of meeting the constraint using other compliance strategies, such as directly improving mileage or selling a larger share of small vehicles. Thus, constrained automakers that exploit the flexible-fuel loophole without hitting the backstop reveal the marginal cost of compliance using these alternative strategies.

E. *Which Models Should Get Flexible-Fuel Capacity?*

We do not attempt to characterize fully the set of models that will receive flexible-fuel capacity, because we do not have the specific engineering cost data needed to test such predictions. We can, however, draw several heuristic points from the model and take these to the data. First, the combination of a fixed cost and constant incremental cost implies that automakers, at the optimum, will outfit just one model with flexible-fuel capacity. They will only consider fitting a second model with flexible-fuel capacity if the first model's flexible-fuel share is 100 percent.

Second, the AMFA formula's flexible-fuel credit mechanically treats inefficient models more generously than efficient ones, so automakers should prefer inefficient models, all else equal. Third, and finally, we can expect firms to choose models with higher sales volumes, because high-volume models allow automakers to relax

[7] Note that we calculate the marginal cost of tightening the CAFE standard while holding the limit on using the flexible-fuel loophole constant. Other policy changes are possible. For example, the marginal benefit of relaxing ϕ is simply μ dollars per vehicle, which we are not able to estimate using our methodology. The marginal cost of increasing σ while simultaneously increasing ϕ by the same amount is λ dollars per vehicle, regardless of whether the backstop is binding or not. Neither of these policy changes is relevant here, as we assume that the backstop constraint is slack, implying that its shadow price is zero.

the constraint further before running up against a second fixed cost. Concentrating flexible-fuel production on a model with high sales volumes might also yield lower prices for parts by inducing competition among suppliers.

We do not observe the fixed or incremental cost of flexible-fuel capacity for individual models. Thus, in the empirical section we only ask if the selection of models is broadly consistent with automakers choosing a minimum number of models (to limit fixed costs) and choosing inefficient models with high sales volumes (to maximize the impact on the constraint).

F. *Extension to Multiple Periods*

Above, we present a static model. This deviates from reality in two important ways. First, CAFE includes banking and borrowing provisions, which allow automakers to carry excess credits or debts for up to three years. Second, automakers must choose vehicle mileage and decide which vehicles will have a flexible-fuel option before production begins, whereas they can adjust prices and flexible-fuel shares at short notice. As a result, if an unexpected shock (e.g., a gasoline price change) shifts demand, automakers may be unable to respond immediately by changing vehicle mileage or enabling flexible-fuel capacity on new models.

In the online Appendix, we demonstrate that the conclusions from the static model extend to a dynamic setting that includes banking and borrowing, lagged choices, and demand shocks. In this dynamic setting, our expression for the shadow price represents both the current shadow price and the expected future shadow price. The online Appendix also describes how a large demand shock might keep the automaker from exhausting the loophole as intended, because of design decisions inherited from a previous period, and we explain why the data suggest that this is not a common occurrence.

G. *Additional Considerations*

Having established our key theoretical results, we now backtrack briefly to tie up several loose ends. Number one: differentiating the automaker's profit function at the optimum by the fuel-economy standard yields the shadow price on the first constraint, which quantifies the automaker's marginal compliance costs in equilibrium. To go further and interpret this value as the marginal loss in profit the firm would suffer if regulators actually tightened the standard, however, one must assume that competitors do not change their prices or mileage in direct response to the policy change; they only respond indirectly to prices and mileage set by the firm we model explicitly. Literally, this means that the parameter we have described is the marginal cost that a firm would incur if regulators raised its fuel-economy standard without raising the standard for other firms bound by the constraint.[8]

[8] Whether our estimate will be larger or smaller than the marginal cost from raising the standard for all firms simultaneously depends on how an index of prices and attributes of competing firms changes with the standard. While it is intuitive to expect that our cost estimates will exceed the cost of raising the standard for all firms since this will harm competitors, the opposite case is possible. The counterintuitive case is similar to the perverse outcomes analyzed in Stephen P. Holland, Jonathan E. Hughes, and Christopher R. Knittel (2009), in which a tighter constraint can cause a firm's average price to decrease. If all firms bound by the constraint produce flexible-fuel vehicles at an interior solution, however, it is reasonable to expect that our results will be correct, since exploiting the flexible-fuel loophole is nearly a constant marginal cost strategy.

Number two: our model assumes that consumers ignore flexible-fuel capacity so that the flexible-fuel and conventional versions of the same model share a single price. In reality, some consumers may prefer flexible-fuel vehicles, while others may dislike them. For our key results to hold, however, we only require that a mass of marginal consumers are indifferent to flexible-fuel capacity. That is, for any model at an interior flexible-fuel share, some mass of indifferent consumers would switch from one configuration to the other if a price difference arose. This is simply a no-arbitrage condition. In the empirical section, we provide support for this assumption.

Number three: while our methodology technically yields the marginal cost of improving AMFA fuel economy, this closely approximates the marginal cost of improving actual fuel economy when the automaker produces a small number of flexible-fuel vehicles. Equation (3) shows that the difference between AMFA fuel economy and actual fuel economy shrinks to zero as sales quantities for flexible-fuel vehicles get small. Formally, suppose the automaker produces only one type of vehicle. Then the first constraint weighted by its shadow price (now in different units, since we drop the Q for clarity) simplifies to

$$\lambda\left[\frac{m}{1 - \theta(1 - \beta)} - \sigma\right], \tag{9}$$

where m is the automaker's actual mileage, θ is its flexible-fuel share, and the first term inside the brackets is the automaker's AMFA mileage. Differentiating with respect to actual mileage gives

$$\frac{\lambda}{1 - \theta(1 - \beta)}, \tag{10}$$

or the marginal benefit of relaxing the constraint by improving actual mileage, which the automaker will set equal to marginal costs. Suppose that θ is small, say 0.15, which is the maximum flexible-fuel share for a binding light-truck standard of miles per gallon and maximum flexible-fuel gain of miles per gallon. Then the marginal cost of improving actual fuel economy exceeds the marginal cost of improving AMFA fuel economy by a factor of just. The maximum flexible-fuel share for cars is even lower than 0.15, and in practice flexible-fuel shares average less than 0.06 during our study period.

Number four: there are three cases in which we are only able to bound marginal compliance costs. First, if the backstop constraint is binding, then the cost of improving fuel economy using the flexible-fuel loophole gives a lower bound on marginal compliance costs, because the shadow price on the backstop constraint is positive. Second, if the automaker runs up against a 100 percent flexible-fuel share, then we also identify a lower bound, since exploiting the loophole further requires paying another fixed cost. Because the automaker complies with the fuel-economy standard, we also know that costs are bounded from above by the level of the fine in both these cases. Third, if a constrained automaker does not produce flexible-fuel vehicles, then the cost of improving fuel economy using flexible-fuel vehicles gives an upper bound on marginal costs. This assumes that fixed costs are zero or that the firm is so large that average fixed costs are effectively zero. Such bounds may be useful in other applications.

Finally, number five: actual fuel-economy standards are more complicated than we describe above. One complication is that automakers also receive extra credit for vehicles that run on natural gas, electricity, or other alternative fuels. These vehicles all contribute toward the backstop limit of 1.2 miles per gallon. We include these vehicles when determining whether automakers are at the backstop but ignore these vehicles otherwise because they account for a tiny fraction of alternative-fuel vehicles.

A second complication is that fuel-economy standards regulate light-duty trucks and passenger cars separately. Passenger cars are further divided into "domestic" and "import" fleets based on where they are produced. All three fleets qualify for the same flexible-fuel incentive, and the limit of 1.2 miles per gallon applies to each fleet separately. Credits may not be transferred across an automaker's fleets or traded from one firm to another.[9] Mathematically, this would imply a constraint on AMFA fuel economy and corresponding shadow price for each fleet, as well as a backstop constraint and corresponding shadow price for each fleet. Each of the above results would apply separately to the three fleets, with marginal costs in expression (8) in terms of costs per domestic car, import car, or light truck. In what follows we distinguish between the light-truck and two passenger-car fleets.

II. Automakers Exploit the Flexible-Fuel Loophole

The previous section showed that we are able to identify the marginal cost of CAFE regulation as long as four sufficient conditions hold. First, constrained automakers must exploit the flexible-fuel loophole to comply with CAFE standards. Second, automakers must offer a model with an interior flexible-fuel share. Third, automakers must not exhaust the flexible-fuel loophole by hitting the backstop constraint. Fourth, and finally, marginal consumers must not value flexible-fuel capacity. We demonstrate that the first, second, and third of these conditions hold using administrative data from the Department of Transportation's National Highway Safety and Transportation Administration (NHTSA). These data record model names, production quantities, AMFA fuel economy, actual fuel economy, fuel type, and other vehicle attributes by model year. NHTSA collects these data to determine whether firms comply with CAFE standards. We demonstrate that the fourth condition holds using vehicle transaction data below.

A. *Automakers Exploit but Do Not Exhaust the Loophole*

Table 1 summarizes fuel-economy performance and flexible-fuel production across automakers from 1993, the model year in which the flexible-fuel loophole came into effect, through 2006. For all three fleets regulated by CAFE standards (i.e., domestic cars, import cars, and light trucks), the table shows an automaker's actual fleet-average fuel economy, the difference between actual fuel economy and the standard, the fraction of the automaker's vehicles that are flexible-fuel vehicles,

[9] Note that trading between automakers and fleets is authorized under legislation passed in 2007.

TABLE 1—FUEL-ECONOMY PERFORMANCE AND FLEXIBLE-FUEL PRODUCTION 1993–2006

	Domestic cars				Import cars			
Firm	Actual mpg	Versus CAFE	FFV share	Paid fine	Actual mpg	Versus CAFE	FFV share	Paid fine
USA								
GM	27.9	0.4	0.6	no	29.9	2.4	·	no
Ford	27.1	−0.4	2.8	no	28.0	0.5	·	no
Chrysler	27.6	0.1	0.8	no	26.4	−1.1	1.4	yes
Europe								
VW	·	·	·	·	28.8	1.3	·	no
BMW	·	·	·	·	25.8	−1.7	·	yes
Mercedes	·	·	·	·	24.9	−2.6	·	yes
Volvo	·	·	·	·	25.7	−1.8	·	yes
Asia								
Toyota	33.0	5.5	·	no	30.4	2.9	·	no
Honda	32.2	4.7	·	no	32.0	4.5	·	no
Nissan	29.1	1.6	·	no	29.2	1.7	·	no
Industry	28.2	0.7	1.1	·	29.2	1.7	0.1	·

	Light trucks				Vehicle shares			
Firm	Actual mpg	Versus CAFE	FFV share	Paid fine	Total market share	Percent domestic cars	Percent imported cars	Percent truck
USA								
GM	20.4	−0.3	6.0	no	29.0	53	2	45
Ford	20.3	−0.4	5.9	no	22.6	41	6	53
Chrysler	20.5	−0.3	6.0	no	15.8	27	7	66
Europe								
VW	19.9	−0.9	·	yes	1.9	·	97	3
BMW	20.6	−0.3	·	yes	1.2	·	87	13
Mercedes	21.3	0.6	·	no	0.3	·	93	7
Volvo	·	·	·	·	0.2	·	100	·
Asia								
Toyota	22.6	1.8	·	no	10.3	15	46	38
Honda	25.0	4.1	·	no	7.2	44	33	23
Nissan	21.5	0.7	1.8	no	5.2	22	39	39
Industry	20.8	0.1	4.7	·	100.0	35	20	45

Notes: The table summarizes fuel-economy performance and flexible-fuel production during the 1993–2006 model years. Total vehicle sales over this period were 210.9 million vehicles. Actual mpg is sales-weighted harmonic-average mileage ignoring flexible-fuel incentives. Fuel economy in excess of the standard is based on firm-specific, sales-weighted standards during the study period because the light-truck standard is increasing over time. The table omits several small European automakers with market shares less than 0.1 percent (e.g., Ferrari) and eight Asian automakers with market shares ranging from 0.1–1.6 percent. (e.g., Hyundai and Subaru). Mercedes and Volvo include only model years 1993–1998, before their mergers with Chrysler and Ford; Chrysler includes Mercedes for 1999–2006, while Ford includes Volvo for 1999–2006. See text for details.

and whether the automaker ever paid a fine between 1993 and 2006. The table also shows each automaker's total production and market share for these model years, as well as the fraction of an automaker's total production in each fleet.

These aggregate data reveal a pattern of flexible-fuel production that appears to be motivated only by CAFE standards. All three domestic automakers produced flexible-fuel vehicles in fleets whose actual mileage was below the standard, including Ford's domestic cars, Chrysler's import cars, and all three truck fleets. With the exception of Chrysler's import fleet during its merger with Mercedes, flexible-fuel vehicles were sufficient to keep all five of these domestic fleets in compliance through the entire period. Chrysler paid fines on its import car fleet briefly during its merger with Mercedes-Benz, which consistently paid fines prior to the merger. The only domestic fleets that did not feature flexible-fuel vehicles during the study period were GM's import cars and Ford's import cars, which were above the standard.[10] These patterns suggest that automakers only produce flexible-fuel vehicles to comply with fuel-economy standards, which is consistent with statements by automakers that flexible-fuel production would fall dramatically if the incentive were eliminated (US Department of Transportation, US Department of Energy, and US Environmental Protection Agency 2002).

The only foreign firm ever to make flexible-fuel vehicles is Nissan, which did not make them until 2005–2006 when its actual light-truck fuel economy fell below the standard (details below). Honda and Toyota, who hold large shares of the American market, and whose average fuel economy is well above the standard, never made flexible-fuel vehicles. If it were profitable to offer flexible-fuel vehicles in the absence of CAFE benefits, it is reasonable to expect that Honda and Toyota would have done so. While European automakers consistently fall short of fuel-economy standards and regularly pay fines, they do not make flexible-fuel vehicles. European firms sell relatively few vehicles in the United States, however, and fixed engineering costs likely exceed the fines they could avoid using flexible-fuel vehicles.

Figures 1–4 provide more detail by plotting AMFA fuel economy (which accounts for the flexible-fuel incentive), actual fuel economy (which ignores the incentive), and fuel-economy standards over time for automakers that produce flexible-fuel vehicles.[11] The figures make clear that US automakers regularly depend on flexible-fuel vehicles to comply with fuel-economy standards. For example, Chrysler would have fallen short of the light-truck standard every year from 1999–2002 were it not for the flexible-fuel loophole (Figure 1a), while Ford would have missed the light-truck standard every year from 1999–2005, save 2001 (Figure 2a). Because automakers can bank or borrow for up to three years, flexible-fuel vehicles that increase fuel economy when an automaker is already above the standard may still be valuable. For example, the flexible-fuel cars Chrysler produced in 2003–2005 made up for deficiencies in its domestic passenger-car fleet in 1999 and 2006 (Figure 1c).[12]

Figures 1–4 also plot the difference between AMFA fuel economy and actual fuel economy in each year, as well as the backstop limit of $\phi = 1.2$ miles per gallon. NHTSA ignores any gain in fuel economy above this threshold when calculating an

[10] Chrysler and GM produced flexible-fuel vehicles in their domestic car fleets, whose actual mileage exceeded the standard on average during 1993–2006. Nevertheless, automakers may have needed (or may have expected to to need) flexible-fuel vehicles to comply, since compliance is actually based on a moving average over a narrower range of years, as we discuss above and below.

[11] Our calculations for AMFA fuel economy include a small number of natural gas vehicles and other alternative-fuel vehicles, which are important for determining whether an automaker is at the backstop. We have omitted figures for Ford and GM's import passenger cars, as well as for Nissan's domestic and import cars, since these fleets do not include any flexible-fuel vehicles.

[12] Note that the fact that automakers did not immediately take advantage of the loophole in the early 1990s is not sufficient to imply that CAFE costs were especially low at that time. Firms likely incurred significant fixed costs in initially learning how to use flexible-fuel technology. Slow entry into the flexible-fuel market may be the result of this learning process.

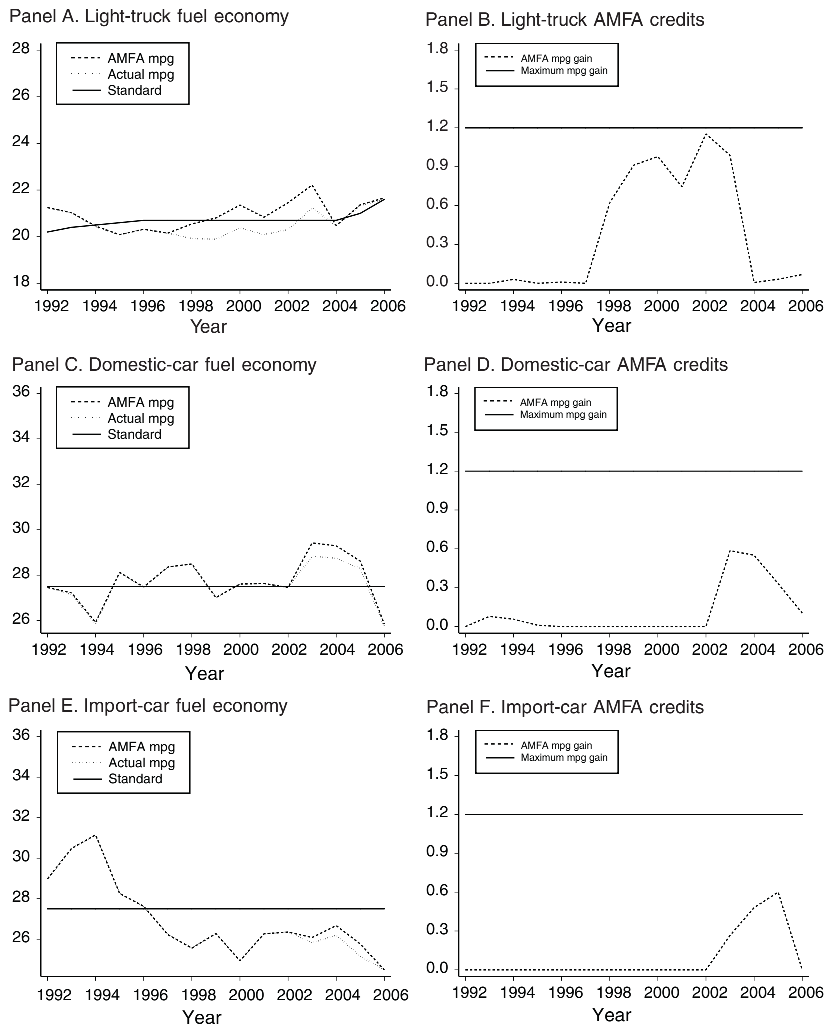

Figure 1. Chrysler Fuel Economy and AMFA Credits

Notes: The panels on the left show AMFA fuel economy, actual fuel economy, and CAFE standards for model years 1992–2006. AMFA incentives began in 1993. The panels on the right show the annual increase in fuel economy due to the AMFA incentive and the 1.2 mpg limit. The regulations ignore any mileage gain above this limit when calculating an automaker's annual fuel economy.

automaker's compliance in a given year, and an automaker is not able to bank or borrow anything above this limit. Automakers therefore have no incentive to produce above the limit unless marginal consumers value flexible-fuel capacity. As expected, automakers rarely exceed this limit. Chrysler came close with its light-truck fleet in 2002 but did not exceed the limit. Ford and General Motors briefly exceeded the limit for their light-truck fleets in 2003–2004 and 2002–2004, but reduced flexible-fuel shares in 2005.[13] GM exceeded the limit with their cars in 2006.

[13] Our transaction data, which we describe below, reveal that Ford and GM produced many flexible-fuel vehicles early in the 2003 and 2004 model years, which is consistent with the automakers being at a corner solution or

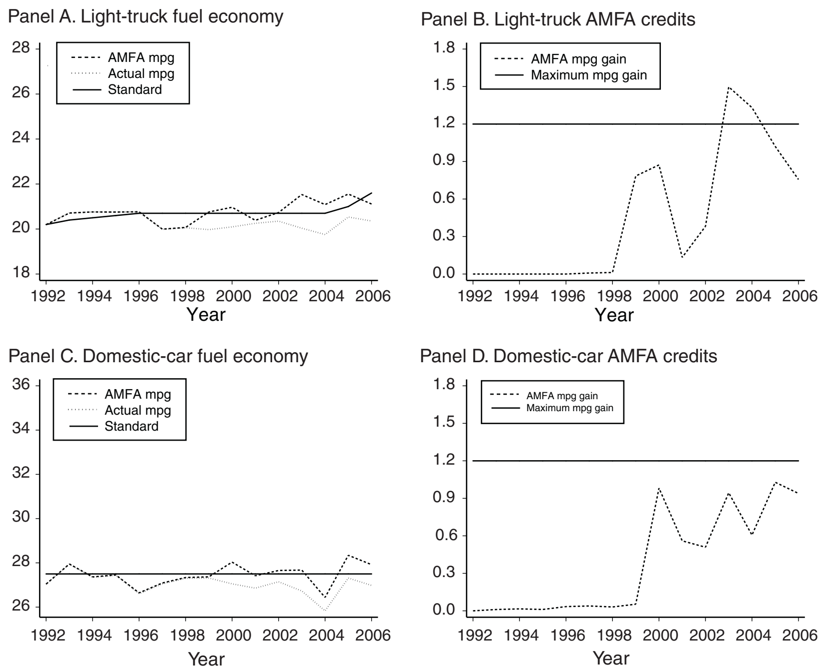

Figure 2. Ford Fuel Economy and AMFA Credits

Notes: The panels on the left show AMFA fuel economy, actual fuel economy, and CAFE standards for model years 1992–2006. AMFA incentives began in 1993. The panels on the right show the annual increase in fuel economy due to the AMFA incentive and the 1.2 mpg limit. The regulations ignore any mileage gain above this limit when calculating an automaker's annual fuel economy.

The gain in mileage from using the flexible-fuel loophole is roughly proportional to the fraction of vehicles with flexible-fuel capacity. This implies, for example, that Chrysler, which earned about 0.5 miles per gallon for its domestic cars using flexible-fuel vehicles in 2004, could have doubled the number of flexible-fuel vehicles it produced that year without exceeding the limit (Figure 1b).

In sum, the figures show that fuel-economy standards were binding for domestic automakers during 1993–2006 and that automakers would have paid fines were it not for flexible-fuel vehicles. The figures also show that automakers rarely exhaust the flexible-fuel loophole in any given year, let alone for the compliance period as a whole. These are two of the four conditions we need.[14]

perhaps misjudging their need for flexible-fuel vehicles early on. They delayed production in 2005–2006 until later in the year when they presumably had better information, however, and could have further increased flexible-fuel shares but did not, which is consistent with an interior solution.

[14] One comment we have received is that CAFE's overall effect may be very large relative to the 1.2 miles per gallon of compliance permitted under the flexible-fuel loophole. If so, then an interior solution would be highly coincidental. This is difficult to judge without knowing how low fuel economy would have been in the absence of the standard. But, we can see from table 1 that most unconstrained Asian and noncompliant European fleets are within a couple miles per gallon of the standard. Assuming domestic automakers would tend toward the middle of the mileage distribution in the absence of CAFE, an interior solution seems plausible.

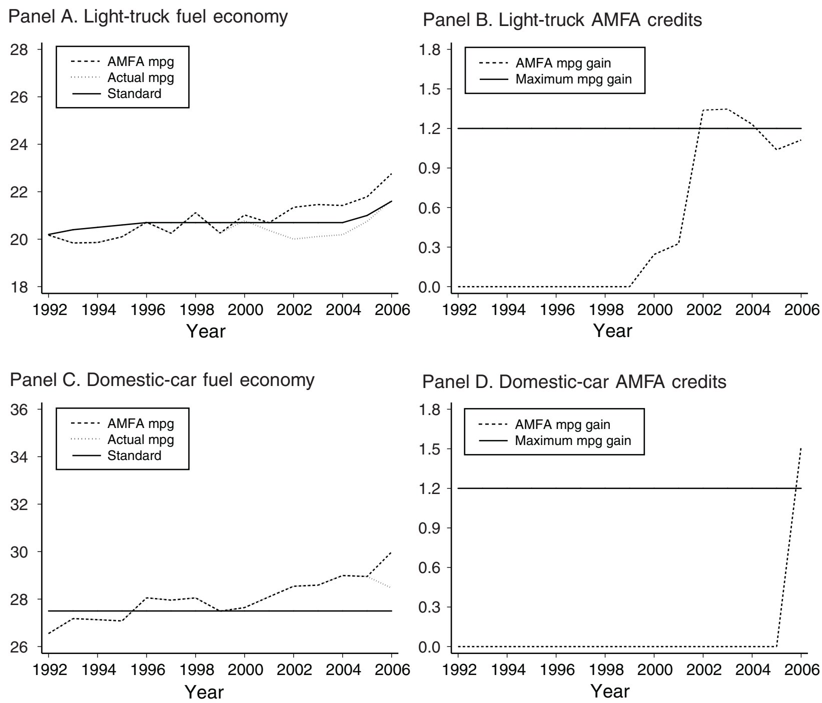

Figure 3. General Motors Fuel Dconomy and AMFA Credits

Notes: The panels on the left show AMFA fuel economy, actual fuel economy, and CAFE standards for model years 1992–2006. AMFA incentives began in 1993. The panels on the right show the annual increase in fuel economy due to the AMFA incentive and the 1.2 mpg limit. The regulations ignore any mileage gain above this limit when calculating an automaker's annual fuel economy.

B. *Automakers Produce Interior Flexible-Fuel Shares on One or Two Engine Sizes*

Our model makes several broad predictions about flexible-fuel shares when automakers exploit the flexible-fuel loophole to comply with CAFE standards. First, automakers will not install flexible-fuel capacity on multiple models if this requires paying multiple fixed costs and if any single model is sufficient. Engineering details that would allow us to classify vehicles precisely by engine types that share fixed costs are not available. It is clear that model name is too narrow for this purpose. Some models with different names are effectively the same vehicle (e.g., the Ford Explorer and Mercury Mountaineer), and many models that are superficially different share the same engine (e.g., the Ford Explorer and Explorer Sport Trac). We therefore use engine size (i.e., displacement) as a proxy to classify vehicles by shared fixed costs. This is an imperfect measure, but it is likely a better measure than model name.

The top half of Table 2 lists, for each automaker and fleet and year, the number of engine sizes that include a flexible-fuel version, as well as the total number of engine sizes that each automaker produces. The table shows that automakers typically install flexible-fuel capacity on only one engine size per fleet, as our model predicts. They never install flexible-fuel capacity on more than two engine sizes.

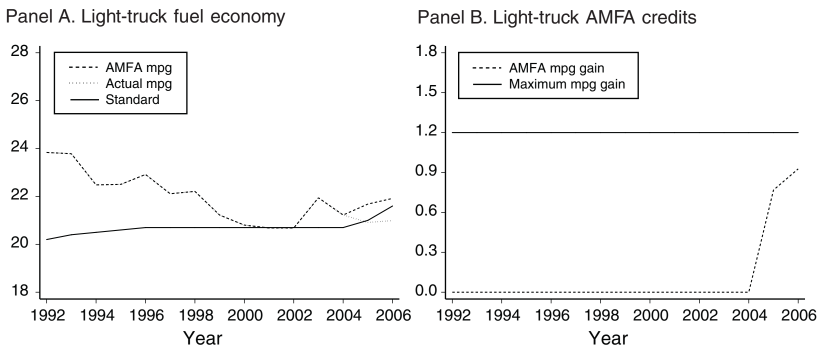

Figure 4. Nissan Fuel Economy and AMFA Credits

Notes: The panel on the left shows AMFA fuel economy, actual fuel economy, and the CAFE standard for model years 1992–2006. AMFA incentives began in 1993. The panel on the right shows the annual increase in fuel economy due to the AMFA incentive and the 1.2 mpg limit. The regulations ignore any mileage gain above this limit when calculating an automaker's annual fuel economy.

Our model also predicts that if incremental costs and fixed engineering costs are the same across models, automakers will tend to install flexible-fuel capacity on inefficient models, as this yields bigger gains in average mileage. Automakers will also tend to install flexible-fuel capacity on models with higher sales volumes. Figure 5 plots flexible-fuel shares and average mileage by engine size for vehicles produced during 1993–2006. Flexible-fuel vehicles are not particularly inefficient relative to other vehicles. Automakers do avoid installing flexible-fuel capacity on models with low sales volumes, which in the figure are proportional to circle sizes.[15] The fact that mileage and sales volume do not precisely predict flexible-fuel status may simply reflect considerable heterogeneity in fixed engineering costs, which are unobservable.

Finally, the bottom half of Table 2 shows that automakers were at interior flexible-fuel shares on nearly every flexible-fuel engine size from 1996–2006. Chrysler was at a corner solution with its trucks in 2002, while General Motors was at a corner solution in 2001, and Ford was near a corner solution in 2000. The remaining cases all have interior flexible-fuel shares, and about three-quarters have flexible-fuel shares below 50 percent. On average for 1993–2006, flexible-fuel shares were under 40 percent for all engine sizes on which automakers installed flexible-fuel capacity. This is the third of four conditions we need to infer the marginal cost of tighter CAFE standards.

The one possible exception to the patterns we have described is the Chrysler import fleet. In 2004–2006, Chrysler installed flexible-fuel capacity on some Mercedes nameplate sedans. They did not hit the backstop constraint, and according to Table 2 they were at an interior solution, yet they did not produce enough flexible-fuel vehicles to meet the standard. As a result, they both paid fines and produced flexible-fuel vehicles, which would be unexpected in our framework unless the backstop were binding. The flexible-fuel models that Mercedes produced in these years, however,

[15] Note that the figure does not control for the number of years that various models were offered, however, so sales volumes for some engine sizes may appear artificially low.

TABLE 2—NUMBER OF ENGINE SIZES WITH FLEXIBLE-FUEL CAPACITY AND THEIR FLEXIBLE-FUEL SHARES

	Chrysler domestic cars	Chrysler imported cars	Chrysler trucks	Ford domestic cars	Ford trucks	GM domestic cars	GM trucks	Nissan trucks
How many engine sizes have flexible-fuel capacity (fraction of fleet total)?								
1996				1/8				
1997				1/6				
1998			1/9	1/6				
1999			1/12	1/6	1/9			
2000			1/13	1/7	1/10		1/10	
2001			1/14	1/6	1/13		1/10	
2002			1/15	1/6	2/11		1/12	
2003	1/6	1/11	1/15	1/7	2/11		1/10	
2004	1/6	2/12	1/11	1/6	1/11		1/12	
2005	1/8	2/9	2/13	1/7	1/10		1/11	1/5
2006	1/6		2/14	2/7	1/9	1/14	1/13	1/5
What are the flexible-fuel shares for engines with flexible-fuel capacity (percent)?								
1996				1				
1997				1				
1998			64	1				
1999			76	1	94			
2000			71	27	98		54	
2001			77	13	10		100	
2002			100	12	6 and 11		43	
2003	35	11	82	21	16 and 62		41	
2004	12	7 and 36	0	15	74		32	
2005	13	5 and 39	0 and 2	23	65		30	29
2006	9		1 and 6	2 and 35	22	47	42	35

Notes: The top half of the table shows the number of engine sizes that have flexible-fuel capacity for each fleet in each year, as well as the total number of engine sizes. The bottom half of the table shows the flexible-fuel shares for these engine sizes. The table omits fleets with no flexible-fuel vehicles.

were only offered as flexible-fuel vehicles. That is, Mercedes was at a corner solution for these models, even though it was not at a corner solution among all vehicles with the same displacement. Thus, if Mercedes had wanted to exploit the flexible-fuel loophole further, it presumably would have had to pay the fixed cost on another model. Importantly, our conclusion that other automakers are at interior flexible-fuel shares would still be true if we classified vehicles by individual model instead of by engine size. This is evident in the next section in which we compare vehicles that are identical on every observable characteristic except flexible-fuel capacity. Note that, in general, there is no reason to expect automakers to equalize the shadow price of CAFE across fleets, since CAFE does not allow trading of credits across fleets during our study period.

In sum, automakers respond as predicted to flexible-fuel incentives, and the first three conditions we need to infer marginal compliance costs typically hold. Year-by-year behavior on occasion violates one of our first three conditions, but, with the exception of Chrysler's import cars during its merger with Mercedes, all automakers and fleets are at interior solutions for the study period taken as a whole. It only remains to show that marginal consumers do not value flexible-fuel capacity.[16]

[16] We have also analyzed, using the transaction data we describe below, the timing of flexible-fuel production relative to conventional vehicles over the model-year cycle. Automakers produce flexible-fuel vehicles throughout the entire model year, but production is weighted more heavily toward the middle and end of the year than for

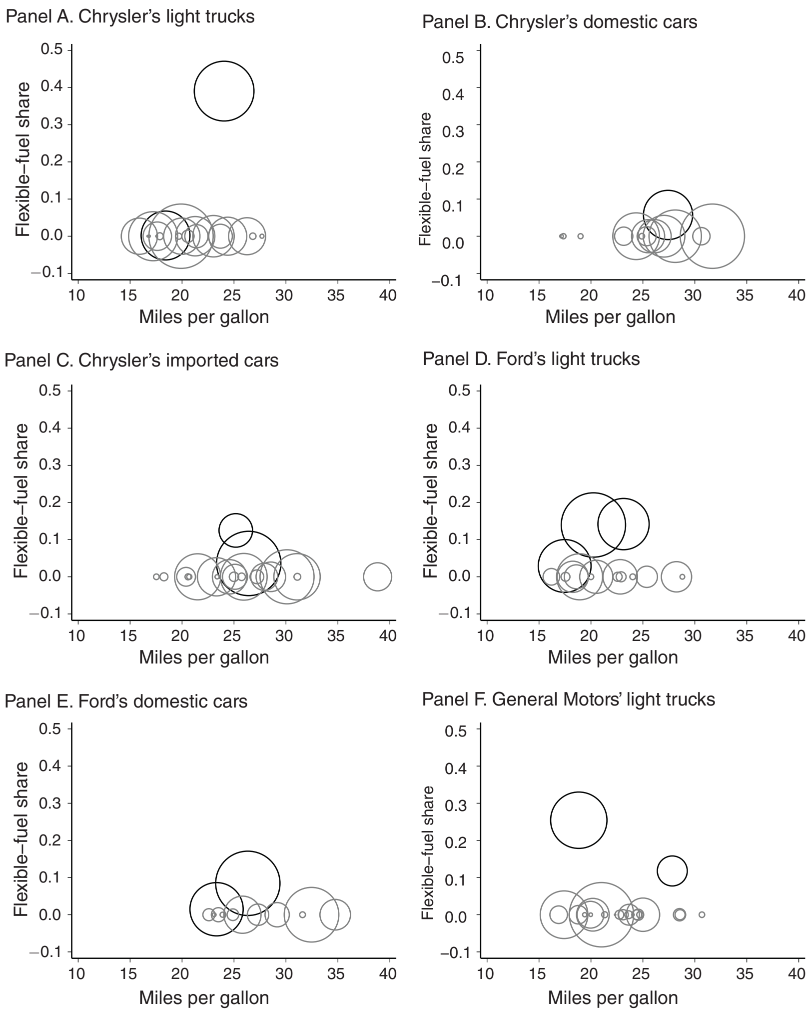

Figure 5. Flexible-Fuel Shares by Engine Size and Fuel Economy

Notes: Figure is based on NHTSA fuel-economy compliance data for 1993–2006 model years. Flexible-fuel share is the fraction of units for each engine size that has flexible-fuel capacity. Miles per gallon is sales-weighted harmonic-average mileage for each engine size. Circle sizes are proportional to sales. Dark circles indicate that flexible-fuel shares exceed zero.

III. Marginal Flexible-Fuel Consumers Do Not Value Flexible-Fuel Capacity

Our model assumes that a small change in a vehicle's flexible-fuel share will not influence demand and that the flexible-fuel and gasoline versions of the vehicle will sell for the same price. Given our other modeling assumptions, this will be true so long as a mass of marginal consumers do not value flexible-fuel capacity; such

conventional vehicles. This is consistent with automakers targeting some overall flexible-fuel share in response to CAFE standards, so that flexible-fuel production rises as the model year progresses and as uncertainty about fleet fuel economy is resolved. Flexible-fuel shares stay well below 100 percent, however, meaning that automakers remain at an interior solution throughout the model year.

consumers will arbitrage away any price differences that arise and will not respond to changes in flexible-fuel shares if prices are equal.

In this section, we provide empirical evidence to support these assumptions. We show that automakers sell many flexible-fuel vehicles to consumers who have little or no access to ethanol. These consumers are unlikely to value flexible-fuel capacity. We also estimate that the price premium for flexible-fuel vehicles is approximately zero. We suspect that some consumers in some states would be willing to pay more for a vehicle with flexible-fuel capacity. The loophole leads automakers to supply flexible-fuel vehicles in such large quantities, however, that many marginal consumers in these states are indifferent. Thus, the price premium is zero in equilibrium, and there is no loss in selling flexible-fuel vehicles in states that have no retail ethanol.

These findings are consistent with evidence that many consumers are unaware that they owned flexible-fuel vehicles, particularly in earlier years. For example, a report by several federal government agencies in 2002 concluded that "many people who have purchased flexible-fuel vehicles do not know they could use E85" (US Department of Transportation, US Department of Energy, and US Environmental Protection Agency 2002), and a major ethanol-producing firm found that 70 percent of flexible-fuel vehicle owners surveyed in 2005 did not know they owned flexible-fuel vehicles.[17]

A. *New Vehicle Transaction Data*

Our vehicle transaction data come from an industry source that collects data directly from a nationally representative sample of dealers. The data contain detailed information on new vehicle prices and characteristics for millions of transactions from 2000 to 2007. In addition to transaction prices, we observe manufacturer rebates, trade-in prices, and trade-in market values, which allow us to adjust prices for rebates and any difference between the price a dealer pays for a trade-in vehicle and the trade-in's actual market value. We also observe interest rates and other information for dealer-financed transactions, allowing us to control for financing incentives.[18] Finally, we observe the calendar date of each transaction and the state in which the transaction took place, as well as the buyer's age and gender. We deflate all prices by the consumer price index for all urban consumers and all items from the US Bureau of Labor Statistics.

To isolate the value of flexible-fuel capacity, we identify flexible-fuel vehicles and comparison vehicles that are identical along every observable dimension, except fuel type. The transaction data include each vehicle's truncated vehicle identification number (VIN), which provides information about a vehicle's make, model,

[17] Matthew L. "Ford to Subsidize Ethanol Pumps in Midwest." *New York Times*. November 5, 2005. http://query.nytimes.com/gst/fullpage.html?res=9D03E3DB173EF937A35752C1A9639C8B63&sec=&spon= (accessed May 28, 2010).

[18] We calculate the value of financing incentives in dealer-financed transactions by comparing a car buyer's actual stream of monthly payments to the payment stream she would have faced at a market interest rate. We calculate actual monthly payments using the loan's size, term, and dealer APR. We calculate an alternative stream of payments using the market-average APR for new car loans through commercial banks from the Federal Reserve Board. The Fed reports average interest rates every three months. We calculate interest rates for intervening months using linear interpolation. Finally, we calculate the present value of each payment stream using a 4 percent annual rate of pure time preference. The value of the financing incentive is the difference between these two present values. These calculations are identical to Carol Corrado, Wendy Dunn, and Maria Otoo (2006).

Table 3—Summary Statistics

Variable	Mean	SD	Minimum	Maximum	Observations
Flexible-fuel vehicle	0.59	0.49	0	1	587,850
Transaction price	31,562	8,390	-10,994	75,002	587,850
Suggested retail price	37,513	8,552	0	206,607	219,861
Manufacturer rebate	2,406	2,017	0	11,409	587,850
Inventory days	72.36	84.94	1	805	569,479
Loan at dealer	0.76	0.43	0	1	511,598
Interest rate (percent APR)	5.48	4.24	0	29.99	382,509
Down payment	7,366	7,416	-10,908	54,285	386,539
Monthly payment	596	197	13.39	3,837	382,509
Loan term (months)	62.34	11.15	12	96	382,509
Trade-in vehicle	0.51	0.50	0	1	587,850
Trade-in balance	1,355	2,737	-23,974	30,170	301,587
Age of buyer	44.68	13.33	16	107	513,462
Female buyer	0.27	0.44	0	1	526,782
Ethanol availability (percent)	0.16	0.65	0	8.11	587,850

Notes: Table shows summary statistics for final estimation sample based on flexible-fuel vehicles and their gasoline-only counterparts. See text for details.

model year, body style, number of doors, drive type, transmission, engine displacement, number of cylinders, and aspiration (e.g., turbo-charged). The data also record each vehicle's fuel type. We focus on flexible-fuel and gasoline vehicles, but the data also include diesels, gasoline-electric hybrids, and other fuel types. Restricting the sample to flexible-fuel vehicles and comparable gasoline vehicles gives an estimation sample of nearly 590,000 observations.[19]

Table 3 presents summary statistics for the estimation sample, while Table 4 lists model names and quantities for flexible-fuel models and comparison vehicles. The detailed transaction data allow us to identify and compare, for example, the price of a gasoline-only 2006 Ford F150 extended-cab pickup with a 5.4L V8 engine and manual transmission to the price of a flexible-fuel 2006 Ford F150 extended-cab pickup with a 5.4L V8 engine and manual transmission. In some cases the data further distinguish between various trim levels and options packages, such as "standard" or "LE." The data do not, however, include information about all the various options that may be installed, such as carpeted floor mats.

In addition to these transaction data, we collect information on ethanol refueling locations from the Department of Energy Alternative Fuels Data Center, which we use to calculate the total number of ethanol stations in each state in each month from 2000 to 2007.[20] We calculate percent ethanol availability by dividing

[19] We first cross-reference fuel types in our data with information from the National Ethanol Vehicle Coalition, which lists model names, years, engine sizes, and VIN identifiers (usually the 8th digit) for flexible-fuel vehicles. We omit models that do not also appear in the Coalition's list, as some vehicles in our sample are actually natural-gas dual-fuel vehicles. Then, for the flexible-fuel vehicles that remain, we attempt to identify comparable gasoline vehicles based on observable characteristics, dropping models for which we are unable to find a match. This gives a preliminary sample of about 750,000 observations. Finally, we omit about 20 percent of these observations, for which we observe more than two VINs per vehicle type, to minimize the chance of unobserved characteristics being correlated with flexible-fuel capacity.

[20] The data do not systematically record open dates, but they do record the date when each station was added to the database. We assume that add dates approximate open dates. The Department of Energy began collecting these data in 1995, and new stations are added regularly, so our calculations based on add dates give a fairly accurate picture of how ethanol availability evolved during our sample period.

Table 4—Flexible-Fuel Models in the Estimation Sample

Model	Gasoline-only	Flexible-fuel	Total
Armada	1,165	1,506	2,671
Aspen	119	565	684
Avalanche	1,473	3,019	4,492
B3000	1,350	773	2,123
Caravan	5,959	11,501	17,460
Cherokee	393	1,311	1,704
Commander	111	667	778
Crown Victoria	85	236	321
Dakota	39	46	85
Durango	46	212	258
Explorer	41,677	50,708	92,385
Express	65	58	123
F150	26,579	26,322	52,901
Grand Marquis	1,471	4,583	6,054
Impala	796	8,180	8,976
Monte Carlo	17	232	249
Mountaineer	6,026	4,647	10,673
Ranger	4,355	1,743	6,098
S10	3,245	6,986	10,231
Sable	870	37	907
Savana	62	12	74
Sebring	3,570	480	4,050
Sierra	6,536	3,289	9,825
Silverado	14,785	7,754	22,539
Sonoma	735	1,680	2,415
Stratus	1,681	11	1,692
Suburban	17,112	53,418	70,530
Tahoe	45,605	75,919	121,524
Taurus	8,454	8,523	16,977
Terraza	149	14	163
Titan	19,926	20,342	40,268
Town Car	1,009	2,585	3,594
Town and Country	2,416	5,089	7,505
Uplander	125	46	171
Voyager	1,509	3,720	5,229
Yukon	24,055	38,066	62,121
Total	243,570	344,280	587,850

Notes: Table shows flexible-fuel models and quantities in estimation sample. Sample excludes flexible-fuel models with a single VIN or more than two VINs per vehicle type. See text for details.

by the total number of retail gasoline stations in each state using information from National Petroleum News.[21]

B. *Many Flexible-Fuel Vehicle Buyers Do Not Have Access to Ethanol*

Our first step is to analyze the relationship between the availability of retail ethanol in a consumer's state of residence and the geographic allocation of flexible-fuel vehicles. Our reasoning is that if a large number of vehicles are sold in states that lack ethanol, it is highly unlikely that marginal consumers anywhere value flexible-fuel

[21] Although National Petroleum News reports data annually, we divide by the mean number of retail gasoline stations in each state from 2000 to 2006, because the data collection process appears to vary from year to year.

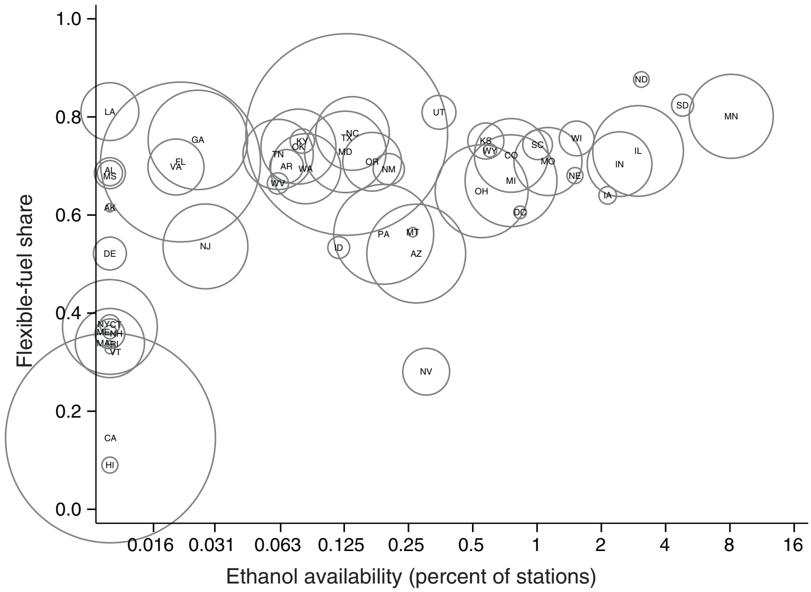

Figure 6. Flexible-Fuel Shares and Ethanol Availability

Notes: Flexible-fuel share is the fraction of vehicles in the estimation sample that have flexible-fuel capacity. Ethanol availability is the maximum fraction of stations that offer ethanol at any time during 2000–2007. Sizes of circles are proportional to the number of observations, and labels are at (or very near, to avoid overlap) circle centers. Figure sets availability to 0.01 percent for 13 states with zero ethanol stations to be compatible with log scaling. These states appear along the left-hand side of the figure. California's peak availability is small but not zero.

capacity. Our analysis indicates that while there is a positive correlation between ethanol availability and flexible-fuel sales across states, this relationship is weak.

Figure 6 plots flexible-fuel shares and peak ethanol availability by state. We calculate flexible-fuel shares based on our estimation sample of flexible-fuel vehicles and comparison gasoline vehicles. Flexible-fuel shares for these vehicles range from 0.6 to 0.8 in most states. Flexible-fuel shares are substantially lower in California, where many flexible-fuel vehicles fail the state's strict emissions laws, and in Hawaii and Nevada. For the remaining states there appears to be a slight positive correlation between flexible-fuel share and ethanol availability, but the correlation is weak. Doubling ethanol's availability ten times over only correlates with a 30 percent increase in flexible-fuel shares, and flexible-fuel shares are high all over the country.

A full 15 percent of the flexible-fuel vehicles in our sample sell in states where ethanol was never available at more than a single station during the study period, while 87 percent sell in states where ethanol was never available at more than 1 percent of stations. It is difficult to imagine that more than a handful of consumers in these states are willing to pay for flexible-fuel capacity. Thus, automakers deciding on how many flexible-fuel vehicles to produce must have expected that the price premium for marginal vehicles would be zero.

We also test the relationship between flexible-fuel quantities and ethanol pumps by regressing our indicator for flexible-fuel capacity on percent ethanol availability, which varies monthly by state, controlling for month and vehicle-specific fixed effects. Table 5 presents the estimation results. The coefficient on ethanol avail-

Table 5—Where Are Flexible-Fuel Vehicles Allocated?

Controls	State dummies excluded (1)	State dummies included (2)
Percent ethanol availability	0.067	0.024
	(0.007)	(0.004)
Observations	587,850	587,850
Groups	448	448
R^2 (within)	0.06	0.14

Notes: Dependent variable equals one if a vehicle has flexible-fuel capacity and zero otherwise. Both regressions include month dummies and vehicle-specific fixed effects, which distinguish by model year. Standard errors in parentheses are clustered by state-month cells. Regressions use the micro transaction data and therefore are sales weighted.

ability in regression (1) implies that increasing ethanol's market penetration in a state by 1 percent correlates with an increase of 0.067 in flexible-fuel shares among flexible-fuel models sold in the state. This relationship might be biased by unobserved determinants of flexible-fuel shares across states, such as California's strict emissions laws. Indeed, regression (2), which includes state dummy variables, finds a somewhat lower correlation of 0.024, though the positive coefficient implies that flexible-fuel shares correlate with differential changes in availability across states over time.[22]

While these coefficient estimates are consistent with automakers allocating vehicles based in part on preferences, flexible-fuel shares are high everywhere, even in states with virtually no ethanol pumps. If automakers are "overproducing" flexible-fuel vehicles to exploit the flexible-fuel loophole, then a mass of marginal consumers in these and other states are unlikely to value flexible-fuel capacity.

C. *Consumers Do Not Pay Extra for Flexible-Fuel Capacity*

If marginal consumers do not value flexible-fuel capacity, then transaction prices should be the same for flexible-fuel vehicles and comparable gasoline vehicles.[23] In contrast, if marginal buyers had some positive willingness to pay, then a zero price difference could not be an equilibrium, since the firm could raise the price of the flexible-fuel version without affecting sales quantities for either of the two versions. Because most flexible-fuel buyers lack access to ethanol, one would expect the equilibrium price of flexible-fuel capacity to be zero. We compare the prices of vehicles with and without flexible-fuel capacity and find that their prices are not statistically different.[24]

[22] We also estimated regression (1) in Table 5 separately for each calendar year in our sample, finding that the correlation ranges from 0.04 to 0.14 in all years but 2000 (when the correlation was 0.32, perhaps due to a small sample size), with a slight downward trend in recent years.

[23] In the presence of price discrimination and local market power in flexible-fuel supply, consumers in states with ethanol availability, such as Minnesota, might pay a premium, even if consumers in other states do not. Note that price discrimination would only work against our statistical test, however, since our null hypothesis is a zero average price difference. Thus, our failure to reject the null supports our modeling assumptions.

[24] Anecdotal evidence from government and media reports suggests that automakers sometimes increased the manufacturer's suggested retail price (MSRP) for flexible-fuel vehicles, but then netted-out these price increases with targeted rebates (US Department of Transportation, US Department of Energy, and US Environmental Protection Agency 2002). In other media reports, automakers claim that they do not pass the cost of flexible-fuel capacity

Table 6—Flexible-Fuel Premium

Controls	All observations (1)	Cash sales only (2)
FFV	−22.07	−38.13
	(28.29)	(60.19)
Observations	230,639	51,026
Groups	44,824	19,557
R^2 (within)	0.00	0.00

Notes: Dependent variable in both regressions is sales price net of manufacturer rebates, financing incentives, and trade-in overallowance. Regression (2) estimates the model using transactions where the purchaser paid cash at the dealer (i.e., did not borrow or lease from the dealer), so financing incentives do not apply. Both regressions control for vehicle-state-month fixed effects. Some such groups contain no variation in flexible-fuel capacity; table gives number of observations and groups that actually contribute toward identification. Standard errors in parentheses are clustered by vehicle-state-month cells; clustering by vehicle-state cells increases standard errors by roughly one half to three quarters. See text for further details.

We estimate the price premium for flexible-fuel vehicles using the following econometric specification:

$$p_{ijst} = \gamma FFV_{ijst} + \delta_{jst} + \epsilon_{ijst}, \tag{11}$$

where p_{ijst} is the sales price that we observe in transaction i for vehicle type j in state s and in month t; FFV_{ijst} is a dummy variable that equals one if the vehicle in the transaction is a flexible-fuel vehicle and zero otherwise; δ_{jst} is a vehicle-state-month fixed effect; and ϵ_{ijst} is an error term. We estimate the model using least-squares estimation and vehicle-state-month fixed effects.

The coefficient of interest is γ. This coefficient is the average price premium for flexible-fuel vehicles relative to comparable gasoline vehicles sold in the same place at the same time, which measures the marginal willingness to pay for flexible-fuel capacity. The vehicle-state-month fixed effects given by δ_{jst} are equivalent to including vehicle, state, and month dummy variables, as well as all relevant two-way and three-way interactions of these variables. The error term ϵ_{ijst} reflects unobserved vehicle characteristics such as carpet floor mats, tinted windows, or other options that do not come standard in observed trim levels. The identification assumption is that this error term is uncorrelated with flexible-fuel capacity, conditional on state, month, and vehicle type: $E[\epsilon_{ijst} | FFV_{ijst}, \delta_{jst}] = 0$.

Table 6 presents the estimation results for the model in equation (11). The coefficient in regression (1) indicates that the marginal consumer demands a $22 price discount to purchase a flexible-fuel vehicle during the sample period, although this

on to consumers (Joe Kohn, "GM: Some SUVs to Use Ethanol," *Automotive News*, June 19, 2000. http://www.autonews.com/apps/pbcs.dll/article?AID=/20000619/ANA/6190763 (accessed May 1, 2008); and Bernardine Williams, "Lucerne Joins GM's Flex-fuel Lineup," *Automotive News*, April 17, 2008. http://www.autonews.com/apps/pbcs.dll/article?AID=/20080417/ANA05/638068968 (accessed May 1, 2008)). We checked the MSRPs of several flexible-fuel vehicles in May 2008 and found that list prices were the same as comparable gasoline vehicles. Near the end of our sample period, GM did initiate an advertising campaign to promote their flexible-fuel vehicles. If this generated increased demand, the price premium might have increased in the years since our sample ended, though it appears from MSRPs that it did not.

Table 7—Are Flexible-Fuel Transactions Different?

	(1) Days on lot	(2) Dealer loan?	(3) Interest rate	(4) Total down	(5) Monthly payment
FFV	-29.43	-0.011	-0.03	46.81	0.03
	(1.07)	(0.003)	(0.03)	(50.34)	(1.08)
Observations	223,007	202,533	150,003	151,394	150,003
Number of groups	43,257	42,091	31,795	32,068	31,795
R^2 (within)	0.01	0.00	0.00	0.00	0.00
	(6) Loan term	(7) Trade auto?	(8) Trade balance	(9) Age of buyer	(10) Female buyer?
FFV	-0.17	-0.0002	-19.13	0.15	-0.001
	(0.08)	(0.0030)	(21.07)	(0.08)	(0.003)
Observations	150,003	230,693	123,685	201,033	206,776
Number of groups	31,795	44,824	29,310	38,493	41,158
R^2 (within)	0.00	0.00	0.00	0.00	0.00

Notes: Dependent variables are: (1) days that vehicle was in dealer's inventory prior to sale; (2) indicator variable that equals one if buyer took out loan from dealer and zero if buyer purchased vehicle with cash; (3) APR interest rate conditional on loan from dealer; (4) down payment conditional on loan from dealer; (5) monthly payment conditional on loan from dealer; (6) loan term in months conditional on loan from dealer; (7) indicator that equals one if buyer sold dealer a trade-in vehicle at time of purchase and zero otherwise; (8) trade-in amount minus trade-in market value conditional on trade-in vehicle; (9) age of first buyer listed on purchase agreement; (10) indictor variable that equals one if first buyer listed is female and zero otherwise. All regressions include vehicle-state-month fixed effects. Some such groups contain no variation in flexible-fuel capacity; table gives number of observations and groups that actually contribute toward identification. Standard errors in parentheses are clustered by vehicle-state-month cells. See text for details.

coefficient is not statistically different from zero.[25] When we restrict the analysis to cash transactions in regression (2), the flexible-fuel premium falls slightly to −\$38 but is statistically indistinguishable from the estimate in regression (1). These results suggest that neither dealer-financed sales nor our adjustment for financing incentives change the estimates appreciably.[26]

If consumers had specific preferences for flexible-fuel vehicles, we would expect these preferences to correlate with consumer characteristics, such as age or income. Similarly, if automakers installed flexible-fuel capacity on models with low-value or high-value options packages, these packages would correlate with consumer characteristics. Either could lead to sorting on observables. To test for such sorting, we use the same econometric specification as in equation (11), using transaction characteristics as our dependent variable instead of price.[27]

Table 7 presents results. The first regression indicates that flexible-fuel vehicles sold 29 days earlier than comparable gasoline vehicles sold in the same state at the

[25] These results are consistent with earlier work by Liu (2007), who estimates flexible-fuel premiums using annual nationwide data for suggested retail prices from 1996 to 2001. She estimates a premium of \$0.37.

[26] A select one-third of observations also include manufacturer-suggested retail prices. Using the same specification, we find that MSRPs are \$154 higher for flexible-fuel vehicles. This would appear to be consistent with anecdotal evidence that some automakers increased MSRPs to reflect incremental costs but then rebated the difference. When we limit our analysis to the MSRP sample, however, transaction prices are still \$121 higher for flexible-fuel vehicles. We are therefore hesitant to read too deeply into this MSRP estimate, as it is likely the result of sample selection.

[27] Sallee (2011) uses a similar approach to test whether Prius buyers who purchased their vehicles when tax incentives were available are different from buyers who purchased their vehicles when incentives were not available.

same time, which is large compared to the sample mean of 72 days. This unexpected result appears to be an artifact of timing. Automakers produce a disproportionate number of flexible-fuel vehicles late in the model year, and vehicles produced late in the year generally spend fewer days in inventory. Indeed, when we control for production month instead of transaction month in our vehicle-state-month fixed effects, we find that flexible-fuel vehicles actually sell later than comparable gasoline vehicles produced at the same time, but only by 5 days.

None of the other transaction characteristics differs meaningfully across the two fuel types. Flexible-fuel buyers are no more or less likely to finance their vehicles through dealers. Interest rates are no different, nor are down payments, monthly payments, or loan durations. Flexible-fuel and gasoline-only buyers trade in used vehicles just as often, and trade-in balances do not differ systematically. Finally, flexible-fuel and gasoline-only buyers are the same age and gender on average. In summary, we detect no meaningful differences between car buyers who purchase flexible-fuel vehicles and those who buy identical gasoline-only vehicles.

Overall, our analysis of prices and quantities suggests that automakers do not charge more for flexible-fuel vehicles, and, more specifically, that the marginal consumer does not value flexible-fuel capacity. This justifies the formulation of our model, which implicitly assumes that consumers ignore flexible-fuel capacity. Thus, we have shown that the four sufficient conditions that enable us to identify marginal compliance costs all hold for domestic automakers in recent years.

IV. Estimating Marginal Compliance Costs

Using our methodology, we now calculate marginal compliance costs for automakers that produced flexible-fuel vehicles. Equation (8) from above, which we repeat here for convenience, shows that the cost per vehicle of marginally increasing the CAFE standard is a function of several readily observable parameters:

$$\frac{\partial \mathcal{L}^*}{\partial \sigma} \frac{1}{Q} = - \frac{\alpha_k \cdot m_k}{M^2(1 - \beta)}, \tag{8}$$

where α_k is the incremental cost of adding flexible-fuel capacity, m_k is actual mileage, M is fleet-average AMFA fuel economy, and β is the AMFA incentive for flexible-fuel vehicles.[28]

We calculate marginal compliance costs separately for each automaker and fleet by plugging in parameter values as follows. For the incremental cost of adding flexible-fuel capacity, we use a range of \$100–\$200 per vehicle, which we think gives a conservatively high estimate of costs.[29] We assume, as above, that the flexible-fuel

[28] In theory, this equation should hold separately for any model at an interior flexible-fuel share. As we showed above, however, an automaker will typically have only one such model per fleet, both in theory and in practice.

[29] Reliable sources put incremental costs as high as \$150–\$300 per vehicle before automakers began producing flexible-fuel vehicles in large quantities (US Environmental Protection Agency 1990) to as low as \$25–\$50 currently (personal communication with Jeff Alson of the US EPA, May 2008), while NHTSA put the range at \$100–\$200 when it ruled to extend the flexible-fuel provision in 2004 (US Department of Transportation 2004). Recent reports in the popular press quoting automakers themselves are consistent with these ranges, with costs ranging from "\$70 to \$100 per vehicle, depending on engine size" (Bernadine Williams, "Lucerne Joins GM's Flex-fuel Lineup," *Automotive News*, April 17, 2008. http://www.autonews.com/apps/pbcs.dll/article?AID=/20080417/ANA05/638068968 (accessed

incentive is $\beta = 0.6$. The two other parameters vary over time, between fleets, and across flexible-fuel models. For flexible-fuel mileage, we calculate the sales-weighted harmonic-average mileage of an automaker's flexible-fuel vehicles, and we calculate fleet-average AMFA mileage as defined above. We calculate marginal compliance costs for each year separately; in several cases these costs constitute a lower bound due to a binding backstop constraint (see Figures 1–4) or 100 percent flexible-fuel share (see Table 2). We also calculate these costs for the study period taken as a whole, using only the years in which an automaker produced flexible-fuel vehicles, and omitting from the calculation those years in which we are able to identify only a lower bound on costs.

Table 8 presents our estimates of marginal compliance costs for the major domestic automakers and Nissan, during the years in which they produced flexible-fuel vehicles. Focusing on the averages over time and looking across all manufacturers, we see that tightening the light-truck standard by one mile per gallon would have cost the automakers roughly \$10–\$27 in lost profit per truck during these years, while tightening the standard for passenger cars would have cost about \$9–\$18 per car. The cost ranges for each automaker derive from the assumed range of \$100–\$200 for incremental production costs, which we think is conservatively high. Compliance costs differ only slightly between automakers and over time because the mileage of flexible-fuel vehicles varies little, as does AMFA mileage. The stability of these estimates is not meant to imply, however, that the marginal cost of complying would have been equally stable if the loophole did not exist. Stability follows from the fact that, as long as firms have not exhausted the loophole, they can comply by increasing or decreasing their flexible-fuel share, which has a roughly constant marginal cost.

For automakers that exhausted the flexible-fuel loophole or hit 100 percent flexible-fuel shares, the table also presents (in parentheses) lower-bound estimates of marginal compliance costs. Costs in these years are bounded from above by the \$55 statutory fine, ignoring any implicit cost for noncompliance. Unfortunately, since we do not observe fixed engineering costs for installing flexible-fuel capacity, our methodology provides no direct estimate of compliance costs for years in which these constrained firms failed to produce any flexible-fuel vehicles at all. Marginal compliance costs are \$55 per vehicle for automakers that serially pay fines, such as BMW, and zero for unconstrained automakers, such as Honda and Toyota, none of whom produce flexible-fuel vehicles.

For comparison, Table 8 also includes estimates from other recent studies.[30] In contrast to our loophole approach, these other papers rely on structural models

May 1, 2008), to "at most a few hundred dollars more per car" (Alexei Barrionuevo and Micheline Maynard, "Dual-Fuel Vehicles Open Mileage Loophole for Carmakers," *New York Times,* August 31, 2006. http://www.nytimes.com/2006/08/31/business/31loophole.html?sq=flex percent20fuel&st=nyt&scp=14 (accessed May 1, 2008). Some sources report costs at "high sales volumes," implying that some cost estimates include average fixed costs. Rubin and Leiby (2000) cite a consulting report from 1995 that estimated fixed costs of \$4.2 million per model annually and incremental production costs of \$240 per vehicle. In 2008 an engineer working on flexible-fuel vehicles for a domestic automaker told us that a range of \$50–\$200 is appropriate. Finally, after-market conversion kits retail for under \$250. Manufacturer costs are presumably lower than after-market conversion prices. These conversion kits are not sanctioned by regulating agencies because the kits may change vehicle emissions.

[30] Not included in the table are the results of Austin and Dinan (2005), whose supply model incorporates detailed engineering data on the cost of fuel-saving technologies (National Academy of Sciences 2002). Dividing their simulated producer losses by the increase in the standard yields costs of \$20 per mpg per vehicle, which is close to what we estimate here.

Table 8—Marginal Compliance Cost per Vehicle of Tightening Fuel-Economy Standards

	Chrysler domestic cars	Chrysler trucks	Ford domestic cars	Ford trucks	GM domestic cars	GM trucks	Nissan trucks
1996			$11–$23				
1997			$9–$18				
1998		$14–$28	$8–$17				
1999		$14–$27	$9–$17	$13–$25			
2000		$13–$26	$8–$16	$12–$25		$15–$31	
2001		$14–$28	$8–$17	$13–$26		($15–$29)	
2002		($13–$26)	$9–$17	$12–$24		($10–$21)	
2003	$8–$16	$13–$25	$8–$17	($11–$22)		($10–$20)	
2004	$8–$16	$10–$19	$9–$19	($11–$23)		($10–$20)	
2005	$8–$17	$13–$26	$8–$17	$11–$21		$10–$20	$10–$19
2006	$13–$26	$12–$24	$8–$15	$10–$20	($8–$16)	$9–$19	$10–$19
Average	$9–$18	$13–$27	$9–$17	$12–$24		$11–$21	$10–$19
CAFE fine	$55	$55	$55	$55	$55	$55	$55
Jacobsen	$373	$157	$52	$251	$438	$264	na
Gramlich	$347	$347	$347	$347	$347	$347	na

Notes: The table shows estimates of marginal compliance costs per vehicle based on equation (8). Ranges assume an incremental cost of $100–$200 for adding flexible-fuel capacity. Parentheses denote lower bounds due to a binding backstop constraint or 100 percent flexible-fuel share; costs in these years are bounded from above by the $55 statutory fine. Average costs for the study period taken as a whole omit these years. Firms that serially pay fines have marginal costs equal to the CAFE fine of $55. The table also includes Jacobsen (2010) and Gramlich (2010) estimates for comparison; Jacobsen (2010) does not distinguish between domestic and import passenger cars when calculating costs, while Gramlich (2009) does not distinguish between domestic automakers or fleets. See text for details.

that require estimates of demand systems, production cost functions, and strong assumptions about the nature of the market equilibrium. Using such a structural approach, Jacobsen (2010) estimates marginal compliance costs for domestic automakers during 1997–2001.[31] He finds that tightening the fuel-economy standard for light trucks by one mile per gallon during this period would have cost domestic automakers $157–$264 per truck, depending on the automaker, while tightening the standard for passenger cars would have cost $52–$438 per car. Gramlich (2010) uses a similar methodology to estimate marginal compliance costs of $347 per vehicle on average for 1971–2007.[32]

These estimates are much higher than the $55 noncompliance penalty, which should in theory serve as a plausible upper bound on compliance costs since automakers could always choose to pay the fine. Several researchers, and the auto industry itself, have argued that true costs exceed the statutory penalty because failing to comply is a civil infraction that could harm an automaker's reputation or make it

[31] Jacobsen first estimates a system of demand elasticities, assumes that oligopolistic automakers engage in Nash-Bertrand pricing behavior, and then solves each automaker's system of first-order conditions to impute markups over full marginal costs (i.e., including CAFE shadow costs). He then assumes that markups over financial costs (i.e., ignoring CAFE shadow costs) are proportional to dealer markups over invoice, which are observed. This allows him to identify CAFE shadow costs by regressing dealer markups on fuel consumption while controlling for imputed markups. The estimated parameter on fuel consumption yields the shadow cost of the fuel-economy constraint. His estimates of the CAFE shadow cost assume that vehicle characteristics are fixed, so that automakers can comply only by selling a larger share of small, efficient vehicles.

[32] Unlike Jacobsen, Gramlich jointly estimates demand and supply. Like Jacobsen, however, he also assumes Nash-Bertrand pricing behavior on the supply side. Because his model of supply explicitly allows automakers to adjust the mileage of each new vehicle, he has additional moment conditions with which to identify the shadow cost of CAFE regulation.

vulnerable to liability claims by shareholders (Kleit 2004; Austin and Dinan 2005; Gramlich 2010; Jacobsen 2010).

There are several reasons to question these large cost estimates and the conventional explanation in recent years. First, European automakers routinely pay fines, and Chrysler recently paid fines on its import fleet. Second, taking these estimates at face value implies massive legal liability and reputation costs. For example, General Motors sold about 5 million vehicles per year from 1997 to 2001, the period of Jacobsen's study. If GM's compliance costs were as high as \$350, which is the average of Jacobsen's car and truck estimates for GM or Gramlich's single estimate, then GM implicitly paid about $(\$350 - \$55) \cdot 5$ million $\approx$ \$1.5 billion per year to avoid violating the standard (by one mile per gallon) and paying the fine. This is a huge price to pay, given that GM averaged about \$5 billion in profits annually during those years. In fact, high compliance costs for GM cars would be especially perplexing during this time period, given that GM produced cars whose actual mileage was well above the standard for much of the last decade and did not resort to producing flexible-fuel cars until 2006. Finally, note that if compliance costs represented billions in lost profit every year, there would have been strong incentives for Japanese automakers, who have sizable CAFE cushions, to merge with the domestic automakers or to buy up brands with large compliance costs, such as Hummer. In the last decade, the only large merger was between Daimler and Chrysler, which offered no CAFE benefit.

There is nothing in our empirical specification that requires our cost estimates to fall below \$55, and we believe the fact that our estimates do fall below this plausible upper bound to be evidence in favor of our methodology. Overall, we think the simplicity and transparency of our approach is appealing in comparison to structural methods.

Our cost estimates do have several limitations. First, and most importantly, our estimates reflect marginal compliance costs during the particular years in our study period, when automakers were producing flexible-fuel vehicles. We are not able to reveal compliance costs for earlier years when the flexible-fuel loophole did not exist, and it is likely that CAFE was more burdensome during times of lower gasoline prices and less advanced technology. Similarly, our cost estimates do not necessarily hold for future years, since gasoline prices, consumer preferences, vehicle attributes, automobile technology, and market structure all evolve over time. The benefit of a more structural approach is that it would have greater external validity in the face of such changes. Second, the structure of CAFE regulation itself is currently in flux: Congress recently set in motion a transition to "size-based" standards, which will require higher mileage for firms that produce smaller vehicles, scheduled a large increase in the standard over the coming decade, expanded the banking-and-borrowing window to five years, and changed the regulation to allow credit transfers across fleets and between firms. These reforms will undoubtedly affect compliance costs.[33] Third, like other estimates in this literature, our estimates reflect the cost of small increases in CAFE standards. Aggressive increases would likely lead to costlier technologies, engineering investments, capital expenditures, and other fixed

[33] Contacts at NHTSA tell us that the expanded banking-and-borrowing window has led to a recent surge in flexible-fuel production in anticipation of more stringent future standards; this recent change in policy is unlikely to have had an impact on automakers during our study period but may be an important consideration moving forward.

costs that our estimates are unable to capture. Finally, our estimates do not reflect changes in consumer surplus resulting from tighter fuel-economy standards.

V. Would Tighter CAFE Standards Increase Welfare?

To put our cost estimates in context, we provide back-of-the-envelope calculations for the marginal external benefits of tighter fuel-economy standards, assuming that automakers are forced to comply by improving actual fuel economy, and ignoring any strategic interactions. Tighter fuel-economy standards reduce US gasoline consumption, which lowers world oil prices, mitigates adjustment costs associated with oil price shocks, and reduces carbon dioxide emissions. Tighter standards reduce the cost of traveling a mile, however, which leads to increased travel and offsetting externalities, including noise, congestion, and traffic accidents.

Conventional estimates for the external damage of greenhouse emissions and other parameters would put costs at roughly \$0.18 per gallon and \$0.10 per mile (Ian Parry, Margaret Walls, and Winston Harrington 2007), and the elasticity response at 0.1 (Kenneth A. Small and Kurt Van Dender 2007). Assuming that the average truck travels 190,000 miles in its lifetime, the external benefit of tightening the standard for light trucks is −\$20 per truck. The external benefit for cars is −\$24 per car, assuming a car travels 162,000 miles.[34] That is, external costs more than offset external benefits. We are unable to perform a formal benefit-cost test, as our cost estimates do not include changes in consumer surplus. Austin and Dinan (2005) and Jacobsen (2010) both find that consumers bear over 80 percent of the welfare loss of tighter standards, however, which suggests that fuel-economy standards are unlikely to pass a benefit-cost criterion, even though the cost to producers is small. Thus, the flexible-fuel loophole may actually increase welfare by allowing firms to relax an inefficient constraint. Of course, relaxing the standard directly would be better than keeping the loophole, as using the loophole to relax the constraint is costly.

We also calculate the implicit carbon price that would have made tighter CAFE standards welfare neutral during our study period, given our cost estimates and assuming that total private losses are five times producer losses. The break-even carbon prices are \$27–\$51 (trucks) and \$48–\$74 (cars) per metric ton of carbon dioxide. While these prices are substantially higher than conventional damage estimates of roughly \$15 per ton (Richard S. J. Tol 2005), the Stern Report (2006) concludes that the benefit of reducing carbon dioxide emissions may be as high as \$85 per ton. Stern's conclusions hinge on assuming extremely low discount rates, but Martin L. Weitzman (2007) has separately concluded that taking into account structural uncertainty about the possibility of catastrophic climate change may lead to similarly

[34] We obtain information on average lifetime miles weighted by survival rates from the US Department of Transportation (2008). The total externality per vehicle is given by $E = c(M/\sigma) + kM$, where c is the marginal external cost of gasoline per gallon, k is the marginal external cost of travel per mile, σ is the fuel-economy standard, and M is miles traveled. Differentiating with respect to the fuel-economy standard and then manipulating terms gives the marginal change in the externality:

$$\frac{\partial E}{\partial \sigma} = -c\frac{M}{\sigma^2}(1 - \xi) + k\frac{M}{\sigma}\xi, \tag{13}$$

where ξ is the elasticity of miles with respect to fuel economy. A negative value implies that tightening the CAFE standard yields net external benefits. Discounting at an annual rate of, say, 3 percent would reduce the magnitude of net benefits by about 20 percent but would not change its sign.

large benefit estimates. In any case, most studies conclude that a higher gasoline tax could achieve the same reduction in fuel consumption as CAFE at much lower cost (National Academy of Sciences 2002; Congressional Budget Office 2003; Austin and Dinan 2005; West and Williams 2005; Jacobsen 2010).

VI. Conclusion

We analyze the market for flexible-fuel vehicles that burn ethanol. While interesting in its own right, this market is especially important because it indirectly provides information about the cost of tightening the fuel-economy standards that apply to all automobiles. Efforts to reduce gasoline consumption in the United States have historically focused on mandating vehicle efficiency through CAFE standards. The merits of these standards are not always clear, in part because it is difficult to measure the cost of regulation in the absence of market prices and because automakers have an incentive to overstate the costs of compliance. Domestic automakers claim that aggressive increases in CAFE standards would cost them tens of billions of dollars in profit, force them to close plants and cut tens of thousands of jobs, increase car prices by thousands of dollars, and "cripple" the domestic auto industry.[35]

We estimate that the marginal compliance cost of the CAFE standard, as revealed by profit-maximizing behavior in the auto industry, was relatively low during much of the last decade. To do so, we demonstrate that automakers exploit an incentive or "loophole" in CAFE regulation that allows them to relax CAFE standards up to a point by producing flexible-fuel vehicles. We show theoretically that constrained automakers will equate the marginal cost of improving fuel economy using flexible-fuel vehicles with the marginal cost of improving fuel economy through other means. Thus, because we can observe the cost of producing a flexible-fuel vehicle, automakers that produce flexible-fuel vehicles without exhausting the loophole indirectly reveal their marginal compliance costs. Based on this approach, we estimate that tightening CAFE standards by one mile per gallon would have cost domestic automakers only \$9–\$27 in profit per vehicle in many recent years. Our estimates are substantially lower than estimates in other recent studies, which use different methodologies and require a broader set of assumptions. Our estimates are also well below the \$55 statutory fine, a plausible upper bound, which has been used as a cost estimate in previous research.

The difficulty of estimating the cost of regulation is not unique to the automobile industry. In most cases, in the absence of a tradable permit system, researchers do not observe compliance costs. Yet loopholes in regulations are as prevalent as regulation itself. In some cases, firms may reveal their marginal compliance costs when they exploit a costly loophole. It is obvious that exploiting a loophole contributes to a firm's overall costs. What is less obvious, but is made clear in our framework, is that the loophole indirectly reveals the marginal cost of conventional compliance strategies. We have proposed several examples beyond the auto industry, including zoning laws,

[35] See Richard Byrne (2003); Bloomberg News. "US Senate Bill Boosts Automobile Mileage, Ethanol," June 22, 2007. http://preview.bloomberg.com/apps/news?pid=newsarchive_en10&sid=a592mVtWF6Zc (accessed May 28, 2010); and David Shepardson, "Auto Lobby Blitzes Senate," *Detroit News,* June 20, 2007. http://www.detnews.com/apps/pbcs.dll/article?AID=/20070620/AUTO01/706200401/1148 (accessed May 23, 2008).

car-pool lanes, and a variety of environmental restrictions, where a loophole-based methodology may prove useful. We suspect that this approach will, at a minimum, complement other methods for estimating the costs of these regulations.

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