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

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Abstract

Automakers can comply with fuel economy regulations by exploiting a loophole that gives a bonus to flexible-fuel vehicles. Under certain conditions, firms will equate the marginal cost of using the loophole, which is observable, with the unobservable costs of other compliance strategies, such as selling smaller cars or upgrading technology. After verifying that these conditions hold empirically, we estimate that tightening standards by one mile per gallon would cost automakers $8–$18 in lost profit per vehicle. Our estimates are considerably lower than other recent estimates based on structural identification. Our approach may help reveal compliance costs for other regulations.

JEL classification numbers: L5, Q5

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1 Introduction

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 would cost domestic automakers between $8 and $28 in profit per vehicle, which is far lower than other recent attempts to measure these costs directly (Jacobsen 2008; Gramlich 2008). 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, 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. 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 (Rubin and Leiby 2000; Liu and Helfand 2008). Our cost estimates fall between zero and $55.

The Alternative Motor Fuels Act (AMFA) modified CAFE regulations starting in 1993

\(^1\)The seminal paper in this literature is 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 Kleit (2004), Austin and Dinan (2005), and West and Williams (2005).
by crediting vehicles capable of burning gasoline and ethanol with about two-thirds better mileage than they actually achieve. These vehicles are known as “flexible-fuel” vehicles.\(^2\) 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 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.

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. Using administrative data from the Department of Transportation, we first show (1) 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 (2) that domestic automakers installed flexible-fuel capacity on some but not all

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\(^2\)Flexible-fuel vehicles can run on a fuel blend known as “E85,” which contains 85% pure ethanol and 15% gasoline. We refer to this fuel as “ethanol” throughout.
units for relevant models, and (3) that they almost never 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 (4) 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 increasing CAFE standards. Compliance costs are a function of a flexible-fuel vehicle’s actual mileage and incremental production cost, which reportedly ranges from $100–$200. For automakers that produce flexible-fuel vehicles, this range implies that tightening the standard for light trucks by one mile per gallon would cost firms $11–$28 in lost profit per truck. Tightening the standard for passenger cars would cost $8–$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. Following our

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3Incentive zoning began in Chicago and New York City, where developers were allowed to exceed height and density restrictions if they provided plaza space (Weiss 1992; Morris 2000). At least half of all cities and
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 U.S. 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 2008), 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.

The remainder of this paper is organized as follows. Section 2 models an automaker’s decision to use the flexible-fuel loophole to relax fuel-economy constraints and establishes towns with zoning laws reportedly have some incentive zoning program (Morris 2000).

4Anderson (2008) shows that demand for ethanol does exist. Since supply is scarce in all but a few locations, however, flexible-fuel owners generally do not have access to ethanol.
sufficient conditions under which we can infer marginal compliance costs. The next several sections demonstrate that these conditions hold empirically. Section 3 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 have not exhausted the flexible-fuel loophole. Section 3 also shows that the set of vehicles we observe with flexible-fuel capacity is broadly consistent with our model’s predictions. Section 4 argues that marginal consumers do not value flexible-fuel capacity. Section 5 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 6 briefly discusses what the results imply about the CAFE program’s net social benefits, and section 7 concludes.

2 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.

2.1 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:

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

where: $M$ 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 $p$ and mileage $m$ for all models of all producers; $c_j$ is the constant marginal cost of the gasoline-only version of the model, which we assuming 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; $\alpha_j$ 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 marginal consumers are indifferent between flexible-fuel vehicles and comparable gasoline vehicles whose prices are equal. Later, we present empirical evidence supporting this claim.

2.2 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:

\[
\frac{1}{\left(\sum_{j \in \mathcal{M}} \frac{q_j(p,m)}{Q} \cdot \theta_j \beta + (1 - \theta_j) \frac{m_j}{m_j}\right)} - \sigma \geq 0,
\]

where \(\sigma\) 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, \(Q = \sum_{j \in \mathcal{M}} q_j(p,m)\) 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 \(\sigma\).

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 \(1/0.6 - 1 \approx 67\%\), 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.

It is convenient to rewrite this first constraint as follows:

\[
\frac{1}{\left(\sum_{j \in \mathcal{M}} \frac{q_j(p,m)}{Q} \cdot \frac{1}{m_j} - (1 - \beta) \sum_{j \in \mathcal{M}} \frac{q_j(p,m)}{Q} \cdot \frac{1}{m_j} \theta_j\right)} - \sigma \geq 0,
\]

which clarifies that flexible-fuel vehicles relax the constraint by reducing sales-weighted average fuel consumption per mile.

\(^5\)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\% higher fuel economy on gasoline or \(1-1/1.35 = 25\%\) lower fuel economy on ethanol. We assume for simplicity that \(r\) is the same for all vehicles so that \(\beta\) is also the same for all vehicles.
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:

\[
1/ \left( \sum_{j \in M} \frac{q_j(p, m)}{Q} \cdot \frac{1}{m_j} \right) - (\sigma - \phi) \geq 0,
\]

(4)

where \( \phi > 0 \) is the limit on using the flexible-fuel incentive, and all other parameters are as above. This constraint requires that actual sales-weighted harmonic-average mileage exceed the less-stringent standard of \( \sigma - \phi < \sigma \). Equivalently, the constraint requires that the automaker’s actual fuel economy not fall short of the nominal fuel-economy standard by more than \( \phi \) miles per gallon. Legislation fixes this limit at \( \phi = 1.2 \) miles per gallon.

2.3 Choosing optimal flexible-fuel shares

It is helpful to think of the automaker as solving a two-stage maximization problem. First, the automaker pays the fixed costs to engineer flexible-fuel capacity on whichever models it chooses. Then the automaker sets flexible-fuel shares for these models. Variable profits in the second stage depend on the combination of models engineered to be flexible-fuel capable in the first stage. Thus, the automaker chooses flexible-fuel models optimally in the first stage to maximize second-stage variable profits minus first-stage fixed costs. 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 second-stage maximization problem is given by:

\[
\mathcal{L} = \sum_{j \in M} \left( p_j - c_j - \alpha_j \theta_j \right) q_j + \lambda \left[ 1/ \left( \sum_{j \in M} \frac{q_j}{Q} \cdot \frac{1}{m_j} \right) - (1 - \beta) \sum_{j \in M} \frac{q_j}{Q} \cdot \frac{1}{m_j} \theta_j \right] - \sigma \] (5)

\[
+ \mu \left[ 1/ \left( \sum_{j \in M} \frac{q_j}{Q} \cdot \frac{1}{m_j} \right) - (\sigma - \phi) \right],
\]
where $\lambda$ and $\mu$ are the shadow prices on the constraints, all other variables are as above, and we have suppressed the arguments of functions for convenience. 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.

2.4 First-order conditions for flexible-fuel shares reveal marginal compliance costs

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

$$-\alpha_k + \lambda \frac{1 - \beta}{m_k Q} M^2 = 0. \quad (6)$$

where $q_k$ factors out of both terms, and $M$ is the automaker’s sales-weighted harmonic-average mileage calculated using flexible-fuel incentives, which is given by the first term 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 flexible-fuel capacity. In the second term, $\beta$ is the share of a flexible-fuel vehicle’s fuel consumption per mile that contributes toward the automaker’s fleet average, so $(1 - \beta)/(m_k Q)$ is the reduction in average fuel consumption per mile from adding flexible-fuel capacity to another unit. The presence of $M^2$ converts this value to a marginal improvement in mileage, and the shadow price on the first constraint $\lambda$ converts this improvement into dollars of marginal benefits. Thus, the automaker simply equates the incremental cost of flexible-fuel capacity with the
marginal benefit of a flexible-fuel vehicle in terms of relaxing the first constraint.\footnote{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.}

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 (6) gives:

$$\lambda = \frac{\alpha}{1/m_k (1-\beta) M^2},$$

which holds with equality for models at an interior flexible-fuel share. The shadow price $\lambda$ on the first constraint equals the incremental cost of adding flexible-fuel capacity divided by the corresponding improvement in 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 (5) at the optimum with respect to the nominal fuel-economy standard gives marginal compliance costs in terms of lost profit:

$$\frac{\partial L^*}{\partial \sigma} = -\lambda - \mu.$$\footnote{Note that we calculate the marginal cost of tightening the CAFE standard $\sigma$ while holding the limit on using the flexible-fuel loophole $\phi$ constant. Other policy changes are possible. For example, the marginal cost of reducing the limit $\phi$ is simply $\mu$, which we are not able to estimate using our methodology. The marginal cost of tightening the CAFE standard $\sigma$ while holding backstop fuel economy $\sigma - \phi$ constant is $\lambda$, 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.}

If the automaker does not exhaust the flexible-fuel loophole, the shadow price on the backstop constraint $\mu$ is zero, and we can ignore the second term. Marginal compliance costs then equal the shadow price on the first constraint only.\footnote{This shadow price is also related to the cost of CAFE standards. Differentiating the automaker’s Lagrangian in equation (5) at the optimum with respect to the nominal fuel-economy standard gives marginal compliance costs in terms of lost profit:}

Substituting for the shadow price using equation (7) and then dividing by total production
yields marginal compliance costs per vehicle as a function of known parameters:

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

(9)

where we have replaced average mileage $M$ with the fuel-economy standard $\sigma$ because the first constraint is binding. Marginal compliance costs are then a simple function of mileage and the incremental cost of adding flexible-fuel capacity for any model with an interior flexible-fuel share. The automaker equates the marginal cost of relaxing the constraint using the flexible-fuel loophole with the marginal cost of meeting the constraint through other means, such as by directly improving mileage or by selling a larger share of small vehicles. Constrained automakers that exploit the flexible-fuel loophole without hitting the backstop therefore reveal their marginal compliance costs.

### 2.5 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%.

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 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).

2.6 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. To go further and interpret this value as the marginal cost to the firm of tightening 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 the government raised its fuel-economy standard without raising the standard for other firms bound by the constraint.

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 analysis 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 with sales quantities for flexible-fuel vehicles. Formally, suppose the automaker produces only one type of vehicle. Then the first constraint weighted by its shadow price simplifies to

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

(10)

where $m$ is the automaker’s actual mileage, $\theta$ 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:

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

(11)

or the marginal benefit of relaxing the constraint by improving actual mileage, which the automaker will set equal to marginal costs. Suppose that $\theta$ is small, say 0.15, which is the maximum flexible-fuel share for a binding light-truck standard of $\sigma = 20.7$ miles per gallon and maximum flexible-fuel gain of $\phi = 1.2$ 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 $1/[0.15 \cdot 0.6 + (1 - 0.15)] \approx 1.06$. 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 two 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. Because the automaker complies with the fuel-economy standard and does not pay fines, we also know that costs are bounded from above by the level of the fine. Second, 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. 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 (9) in terms of costs per domestic car, import car, or light truck. In what follows we distinguish between the light-truck fleet and two passenger-car fleets.

A third and final complication is that fuel-economy regulations allow “banking” and “borrowing.” An automaker that exceeds the standard in one year earns credits that it can use to comply in an earlier or future year to avoid paying fines. Banked credits expire after three years. If the automaker does not have banked credits, it can borrow credits in the short term and earn the credits back in a subsequent year. It must earn the credits back within three years to avoid paying fines. Fines are $55 for every mile per gallon below the standard and scale with total production. Credits may not be transferred across an automaker’s fleets or traded from one firm to another. Moreover, a model’s “year” itself is a choice parameter that automakers can manipulate to comply with fuel-economy regulations.

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8These provisions have recently changed. In 2007, Congress expanded the banking and borrowing window from three to five years and authorized credit transfers across fleets and between automakers.
3 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.

3.1 Constrained automakers exploit the flexible-fuel loophole to comply with CAFE standards 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, 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.
Table 1: Fuel-economy performance and flexible-fuel production 1993–2006

<table>
<thead>
<tr>
<th>Firm</th>
<th>Domestic cars</th>
<th>Import cars</th>
<th>Light trucks</th>
<th>All vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%of sales</td>
<td>act mpg</td>
<td>std share</td>
<td>%ffv share</td>
</tr>
<tr>
<td>USA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GM</td>
<td>53</td>
<td>27.9</td>
<td>0.4</td>
<td>no</td>
</tr>
<tr>
<td>Ford</td>
<td>41</td>
<td>27.1</td>
<td>-0.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Chrysler</td>
<td>27</td>
<td>27.6</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Europe</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BMW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mercedes</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Volvo</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Asia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toyota</td>
<td>15</td>
<td>33.0</td>
<td>5.5</td>
<td>- no</td>
</tr>
<tr>
<td>Honda</td>
<td>41</td>
<td>32.1</td>
<td>4.6</td>
<td>- no</td>
</tr>
<tr>
<td>Nissan</td>
<td>21</td>
<td>29.4</td>
<td>1.9</td>
<td>- no</td>
</tr>
<tr>
<td>Industry</td>
<td>35</td>
<td>28.2</td>
<td>0.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Note: The table summarizes fuel-economy performance and flexible-fuel production during the 1993–2006 model years. 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% (e.g., Ferrari) and eight Asian automakers with market shares ranging from 0.1%–1.6% (e.g., Hyundai and Subaru). Mercedes and Volvo only include 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.
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, but only in fleets whose actual mileage was below the standard. With the exception of Chrysler’s import fleet during its merger with Mercedes, these flexible-fuel vehicles were sufficient to keep each domestic fleet 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 domestic cars, GM’s import cars, and Ford’s import cars, all three of which were above the standard. This suggests 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 (U.S. Department of Transportation, U.S. Department of Energy and U.S. 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.\footnote{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 cars. These are small fleets that do not include any flexible-fuel vehicles, though Ford’s import cars earned AMFA credits} The figures make
clear that U.S. 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).

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 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, but reduced flexible-fuel shares in 2005.\(^{10}\)

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

\(^{10}\)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 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.
Figure 1: Chrysler fuel economy and AMFA credits

(a) Light-truck fuel economy

(b) Light-truck AMFA credits

(c) Domestic-car fuel economy

(d) Domestic-car AMFA credits

(e) Import-car fuel economy

(f) Import-car AMFA credits

Note: The figures on the left show AMFA fuel economy, actual fuel economy, and CAFE standards for model years 1992–2006. AMFA incentives began in 1993. The figures 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.
Figure 2: Ford fuel economy and AMFA credits

(a) Light-truck fuel economy
(b) Light-truck AMFA credits
(c) Domestic-car fuel economy
(d) Domestic-car AMFA credits

Note: The figures on the left show AMFA fuel economy, actual fuel economy, and CAFE standards for model years 1992–2006. AMFA incentives began in 1993. The figures 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.
Figure 3: General Motors fuel economy and AMFA credits

(a) Light-truck fuel economy

(b) Light-truck AMFA credits

(c) Domestic-car fuel economy

(d) Domestic-car AMFA credits

Note: The figures on the left show AMFA fuel economy, actual fuel economy, and CAFE standards for model years 1992–2006. AMFA incentives began in 1993. The figures 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.
Figure 4: Nissan fuel economy and AMFA credits

(a) Light-truck fuel economy

(b) Light-truck AMFA credits

(c) Import-car fuel economy

(d) Import-car AMFA credits

Note: The figures on the left show AMFA fuel economy, actual fuel economy, and CAFE standards for model years 1992–2006. AMFA incentives began in 1993. The figures 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.
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.\textsuperscript{11,12} These are two of the four conditions we need.

### 3.2 Automakers are at interior flexible-fuel shares and rarely install flexible-fuel capacity on more than one engine type

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-

\textsuperscript{11}One comment we have received is that perhaps automakers did intend to exhaust the loophole in most years and were only below the limit due to uncertainty over final sales volumes. This would imply that automakers are effectively at the upper-limit corner solution, at least in expectation, in which case marginal costs may be much higher than we estimate here. If this were the case, however, we would expect to see automakers “miss high” more often than they “miss low.”

\textsuperscript{12}Another 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.
Table 2: Number of engine sizes with flexible-fuel capacity and their flexible-fuel shares

<table>
<thead>
<tr>
<th>Year</th>
<th>Chrysler Dom. cars</th>
<th>Chrysler Imp. cars</th>
<th>Chrysler Trucks</th>
<th>Ford Dom. cars</th>
<th>Ford Trucks</th>
<th>Gen. Motors Trucks</th>
<th>Nissan Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>1/8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>1/6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>1/9</td>
<td>1/6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>1/12</td>
<td>1/6</td>
<td>1/9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>1/13</td>
<td>1/7</td>
<td>1/10</td>
<td>1/10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>1/14</td>
<td>1/6</td>
<td>1/13</td>
<td>1/10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>1/15</td>
<td>1/6</td>
<td>2/11</td>
<td>1/12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>1/6</td>
<td>1/11</td>
<td>1/15</td>
<td>1/7</td>
<td>2/11</td>
<td>1/10</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>1/6</td>
<td>2/12</td>
<td>1/11</td>
<td>1/6</td>
<td>1/11</td>
<td>1/12</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>1/8</td>
<td>2/9</td>
<td>2/13</td>
<td>1/7</td>
<td>1/10</td>
<td>1/11</td>
<td>1/5</td>
</tr>
<tr>
<td>2006</td>
<td>1/6</td>
<td>2/14</td>
<td>2/7</td>
<td>1/9</td>
<td>1/13</td>
<td>1/5</td>
<td></td>
</tr>
</tbody>
</table>

How many engine sizes have flexible-fuel capacity (fraction of fleet total)?

What are the flexible-fuel shares for engines with flexible-fuel capacity (percent)?

<table>
<thead>
<tr>
<th>Year</th>
<th>Chrysler Dom. cars</th>
<th>Chrysler Imp. cars</th>
<th>Chrysler Trucks</th>
<th>Ford Dom. cars</th>
<th>Ford Trucks</th>
<th>Gen. Motors Trucks</th>
<th>Nissan Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1998</td>
<td>64</td>
<td>1</td>
<td>87</td>
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<td></td>
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</tr>
<tr>
<td>2000</td>
<td>71</td>
<td>28</td>
<td>98</td>
<td>54</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>77</td>
<td>13</td>
<td>10</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>100</td>
<td>12</td>
<td>6 &amp; 11</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>35</td>
<td>11</td>
<td>82</td>
<td>21</td>
<td>16 &amp; 62</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>12</td>
<td>7 &amp; 36</td>
<td>0</td>
<td>15</td>
<td>74</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>12</td>
<td>4 &amp; 38</td>
<td>0 &amp; 2</td>
<td>23</td>
<td>65</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>2006</td>
<td>9</td>
<td>1 &amp; 6</td>
<td>2 &amp; 42</td>
<td>22</td>
<td>42</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>

Note: 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.

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. 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 2003, 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 over four-fifths have flexible-fuel shares below 50%. On average for 1993–2006, flexible-fuel shares were under 40% 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, 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. 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 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.
**Figure 5:** Flexible-fuel shares by engine size and fuel economy

(a) Chrysler’s light trucks

(b) Chrysler’s domestic cars

(c) Chrysler’s imported cars

(d) Ford’s light trucks

(e) Ford’s domestic cars

(f) General Motors’ light trucks

Note: 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.
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.\footnote{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 conventional vehicles. This is consistent with the view that automakers target 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.}

4 Marginal flexible-fuel consumers do not value flexible-fuel capacity

In this section we provide empirical evidence based on new vehicle transactions that marginal consumers do not value flexible-fuel capacity. Rosen (1974) shows that what matters for equilibrium prices in a hedonic framework is the valuation of marginal agents. We suspect that some consumers would pay more for a vehicle with flexible-fuel capacity, but that the flexible-fuel loophole leads automakers to supply flexible-fuel vehicles in sufficiently large quantities that a mass of marginal consumers are indifferent. We show that automakers sell many flexible-fuel vehicles to consumers who have 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. If marginal consumers ignore flexible-fuel capacity, then there should be no difference in average price between flexible-fuel vehicles and similar conventional vehicles, all else equal. We are unable to reject this null hypothesis, which supports our conclusion.

These findings are consistent with evidence that many consumers are unaware that they...
own 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” (U.S. Department of Transportation et al. 2002), and a major ethanol-producing firm found that 70% of flexible-fuel vehicle owners surveyed in 2005 did not know they owned flexible-fuel vehicles (Wald 2005).

4.1 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 2000–2007. 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.\textsuperscript{15} 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 U.S. 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, model year, body style, number of

\textsuperscript{15}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% 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 Corrado, Dunn and Otoo (2006).
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.\textsuperscript{16}

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’s Alternative Fuels Data Center, which we use to calculate the total number of ethanol stations in each state in each month from 2000–2007.\textsuperscript{17} We calculate percent ethanol availability by dividing by the total number of retail gasoline stations in each state using information from National Petroleum News.\textsuperscript{18}

\textsuperscript{16}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\% 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.

\textsuperscript{17}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.

\textsuperscript{18}Although National Petroleum News reports data annually, we divide by the mean number of retail gasoline stations in each state from 2000–2006, because the data collection process appears to vary from year to year.
Table 3: Summary statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>flexible-fuel vehicle</td>
<td>0.59</td>
<td>0.49</td>
<td>0</td>
<td>1</td>
<td>587,850</td>
</tr>
<tr>
<td>transaction price</td>
<td>31,562</td>
<td>8,390</td>
<td>-10,994</td>
<td>75,002</td>
<td>587,850</td>
</tr>
<tr>
<td>suggested retail price</td>
<td>37,513</td>
<td>8,552</td>
<td>0</td>
<td>206,607</td>
<td>219,861</td>
</tr>
<tr>
<td>manufacturer rebate</td>
<td>2,406</td>
<td>2,017</td>
<td>0</td>
<td>11,409</td>
<td>587,850</td>
</tr>
<tr>
<td>inventory days</td>
<td>72.36</td>
<td>84.94</td>
<td>1</td>
<td>805</td>
<td>569,479</td>
</tr>
<tr>
<td>loan at dealer</td>
<td>0.76</td>
<td>0.43</td>
<td>0</td>
<td>1</td>
<td>511,598</td>
</tr>
<tr>
<td>interest rate (% APR)</td>
<td>5.48</td>
<td>4.24</td>
<td>0</td>
<td>29.99</td>
<td>382,509</td>
</tr>
<tr>
<td>down payment</td>
<td>7,366</td>
<td>7,416</td>
<td>-10,908</td>
<td>54,285</td>
<td>386,539</td>
</tr>
<tr>
<td>monthly payment</td>
<td>596.40</td>
<td>197.28</td>
<td>13.39</td>
<td>3,836.90</td>
<td>382,509</td>
</tr>
<tr>
<td>loan term (months)</td>
<td>62.34</td>
<td>11.15</td>
<td>12</td>
<td>96</td>
<td>382,509</td>
</tr>
<tr>
<td>trade-in vehicle</td>
<td>0.51</td>
<td>0.50</td>
<td>0</td>
<td>1</td>
<td>587,850</td>
</tr>
<tr>
<td>trade-in balance</td>
<td>1,355</td>
<td>2,737</td>
<td>-23,974</td>
<td>30,170</td>
<td>301,587</td>
</tr>
<tr>
<td>age of buyer</td>
<td>44.68</td>
<td>13.33</td>
<td>16</td>
<td>107</td>
<td>513,462</td>
</tr>
<tr>
<td>female buyer</td>
<td>0.27</td>
<td>0.44</td>
<td>0</td>
<td>1</td>
<td>526,782</td>
</tr>
<tr>
<td>ethanol availability (%)</td>
<td>0.16</td>
<td>0.65</td>
<td>0</td>
<td>8.11</td>
<td>587,850</td>
</tr>
</tbody>
</table>

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

4.2 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 value flexible-fuel 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 0.6–0.8 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
### Table 4: Flexible-fuel models in the data sample

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

Note: 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.
Figure 6: Flexible-fuel shares and ethanol availability

Note: 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. Figure sets availability to 0.01% 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.

correlates with a 30% increase in flexible-fuel shares, and flexible-fuel shares are high all over the country.

A full 15% 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% sell in states where ethanol was never available at more than 1% 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
Table 5: Where are flexible-fuel vehicles allocated?

<table>
<thead>
<tr>
<th>Controls</th>
<th>(1) State dummies excluded</th>
<th>(2) State dummies included</th>
</tr>
</thead>
<tbody>
<tr>
<td>percent ethanol availability</td>
<td>0.069 (0.007)</td>
<td>0.030 (0.005)</td>
</tr>
<tr>
<td>observations</td>
<td>587,850</td>
<td>587,850</td>
</tr>
<tr>
<td>groups</td>
<td>448</td>
<td>448</td>
</tr>
<tr>
<td>R-squared (within)</td>
<td>0.03</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Note: Dependent variable equals one if a vehicle has flexible-fuel capacity and zero otherwise. Both regressions include year dummies and vehicle-specific fixed effects, which distinguish by model year. Standard errors in parentheses are clustered by state-month cells.

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 year and vehicle-specific fixed effects. Table 5 presents the estimation results. The coefficient on ethanol availability in regression (1) implies that increasing ethanol’s market penetration in a state by 1% correlates with an increase of 0.069 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 0.030, though the positive coefficient implies that flexible-fuel shares correlate with differential changes in availability across states over time.

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.
4.3 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. Because most flexible-fuel buyers lack access to ethanol, one would expect the equilibrium price of flexible-fuel capacity to be zero. In the presence of market power or price discrimination, however, consumers in states with ethanol availability, such as Minnesota, might pay a premium, even if marginal consumers in other states do not. We compare the prices of vehicles with and without flexible-fuel capacity and find that their prices are not statistically different.\textsuperscript{19}

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

\[ p_{ijst} = \gamma_{FFV_{ijst}} + \delta_{jst} + \epsilon_{ijst}, \]

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; \( \delta_{jst} \) is a vehicle-state-month fixed effect; and \( \epsilon_{ijst} \) is an error term. We estimate the model using least-squares estimation and vehicle-state-month fixed effects.

The coefficient of interest is \( \gamma \). 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 \( \delta_{jst} \) 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 \( \epsilon_{ijst} \) reflects unobserved vehicle characteristics such as carpet floor mats, tinted windows, or other options that do not come standard in observed trim levels. The

\textsuperscript{19}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 (U.S. Department of Transportation et al. 2002). In other media reports, automakers claim that they do not pass the cost of flexible-fuel capacity on to consumers (Kohn 2000; Williams 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.
Table 6: Flexible-fuel premium

<table>
<thead>
<tr>
<th>Controls</th>
<th>(1) All observations</th>
<th>(2) Cash sales only</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFV</td>
<td>-22.07</td>
<td>-38.13</td>
</tr>
<tr>
<td></td>
<td>(28.29)</td>
<td>(60.19)</td>
</tr>
<tr>
<td>observations</td>
<td>230,639</td>
<td>51,026</td>
</tr>
<tr>
<td>groups</td>
<td>44,824</td>
<td>19,557</td>
</tr>
<tr>
<td>R-squared (within)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Note: 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.

Identification assumption is that this error term is uncorrelated with flexible-fuel capacity, conditional on state, month, and vehicle type: \( E[\epsilon_{ijst} | FFV_j, \delta_{jst}] = 0. \)

Table 6 presents the estimation results for the model in equation (12). 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 coefficient is not statistically different from zero.\(^{20}\) 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.\(^{21}\)

\(^{20}\) These results are consistent with earlier work by Liu (2007), who estimates flexible-fuel premiums using annual nationwide data for suggested retail prices from 1996–2001. She estimates a premium of $0.37.

\(^{21}\) A select one-third of observations also include manufacturer-suggested retail prices. Using the same specification, we find that MSRP are $154 higher for flexible-fuel vehicles. This would appear to be consistent with anecdotal evidence that some automakers increased MSRP 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
Table 7: Are flexible-fuel transactions different?

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

Note: 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) inditector 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.

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 (12), using transaction characteristics as our dependent variable instead of price.\textsuperscript{22}

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 same time, which is large compared to the sample mean of 72 days. This unexpected result appears to be an

\textsuperscript{22}Sallee (2008) 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.
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 differ 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 that purchase flexible-fuel vehicles and those that 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.

5 Estimating marginal compliance costs

Using our methodology, we now calculate marginal compliance costs for automakers that produced flexible-fuel vehicles. Equation (9) from above, which we repeat here for convenience, shows that the cost per vehicle of marginally increasing the CAFE standard is a
function of both flexible-fuel vehicle attributes and regulatory parameters:

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

(13)

where $\alpha_k$ is the incremental cost of adding flexible-fuel capacity, $m_k$ is actual mileage, $\sigma$ is the nominal fuel-economy standard, and $\beta$ is the AMFA incentive for flexible-fuel vehicles.\(^{23}\)

We calculate marginal compliance costs 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.\(^{24}\) Other parameters also vary over time and across flexible-fuel models, but automakers are able to average compliance costs over time. We therefore calculate relevant mileage as the sales-weighted harmonic-average mileage of an automaker’s flexible-fuel vehicles. We assume, as above, that the flexible-fuel incentive is $\beta = 0.6$. Finally, while the standard for passenger cars remains 27.5 miles per gallon during the entire study period, the light-truck standard increases gradually from 20.4–21.6 miles per gallon. We therefore calculate a single, sales-weighted harmonic-average standard for each automaker, weighting the standard in each year by the automaker’s light-truck sales in that year. We calculate costs separately for the light-truck and passenger-car fleets.

Table 8 presents our estimates of marginal compliance costs for the major domestic

\(^{23}\)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 only have one such model per fleet, both in theory and in practice.

\(^{24}\)Reliable sources put incremental costs as high as $\$150–$300 per vehicle before automakers began producing flexible-fuel vehicles in large quantities (U.S. Environmental Protection Agency 1990) to as low as $\$25–$50 currently (personal communication with Jeff Alson of the U.S. EPA, May 2008), while NHTSA put the range at $\$100–$200 when it ruled to extend the flexible-fuel provision in 2004 (U.S. 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” (Williams 2008), to “at most a few hundred dollars more per car” (Barrionuevo and Maynard 2006). 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.
automakers and Nissan, who all produce flexible-fuel vehicles. Tightening the light-truck standard by one mile per gallon would cost these automakers $11–$28 in lost profit per truck, while tightening the standard for passenger cars would cost $8–$19 per car. The ranges for each automaker derive from the assumed range of $100–$200 for incremental production costs, which we think is conservatively high. Costs are not identical because the mileage of flexible-fuel vehicles varies from automaker to automaker, as does the average light-truck standard. We do not calculate compliance costs on a year-by-year basis, because banking and borrowing provisions allow automakers to smooth marginal compliance costs over time.
Nissan first produced flexible-fuel trucks in 2005–2006, revealing marginal compliance costs for at least those years. General Motors first began producing flexible-fuel cars in the 2007 model year. Assuming that the domestic passenger-car standard is binding for General Motors toward the end of the study period, and that General Motors applied flexible-fuel capacity to cars with average mileage, then our methodology implies that GM’s marginal cost of compliance is $9–$18 per car. 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.

Again, because the automaker is optimizing on the margin, these costs equal the marginal cost of improving AMFA fuel economy using flexible-fuel vehicles, as well as the marginal cost of improving AMFA fuel economy through other means. Our estimates therefore reflect lower profit margins on smaller, more efficient vehicles, as well as the difference between production costs and willingness to pay for improvements in vehicle efficiency.\textsuperscript{25}

For comparison, table 8 also includes estimates from other recent studies.\textsuperscript{26} In contrast to our loophole approach, these other papers rely on structural models that require estimates of demand systems, production cost functions, and strong assumptions about the nature of the market equilibrium. Jacobsen (2008) estimates marginal compliance costs for domestic automakers during 1997–2001 based on estimated demand elasticities and observed dealer markups.\textsuperscript{27} He finds that tightening the fuel-economy standard for light trucks by one mile per gallon would cost domestic automakers $169–$456 per truck, depending on the

\textsuperscript{25}Recall that while AMFA and actual fuel economy are not exactly the same, they are quite close in practice, differing by only a few percent.

\textsuperscript{26}Not included in the table are the results of Austin and Dinan (2005), who simulate the effects of tighter standards using a model that allows automakers both to adjust prices and to make vehicles more efficient. Their model of supply 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.

\textsuperscript{27}He 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 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 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.
automaker, while tightening the standard for passenger cars would cost $66–$580 per car. Gramlich (2008) uses a similar methodology to estimate marginal compliance costs of $348 per vehicle on average for 1971–2007.\footnote{Unlike Jacobsen, he jointly estimates demand and supply, but 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.}

These estimates are much higher than the $55 noncompliance penalty, which should 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 vulnerable to liability claims by stockholders (Kleit 2004; Austin and Dinan 2005; Jacobsen 2008; Gramlich 2008).

There are several reasons to question these large cost estimates and the conventional explanation. First, European automakers routinely pay fines, and Chrysler has 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 4 million vehicles in the United States in 2007. If compliance costs were as high as $355, which is roughly the median estimate from these other papers, then GM implicitly paid $1.2 billion per mile per gallon extra in 2007 to avoid violating the standard and paying a fine.\footnote{In GM’s five most recent profitable years, it averaged under $2.5 billion annually in profits, which implies that $1.2 billion per mile per gallon is also quite large in relative terms.} In fact, high compliance costs for GM would be especially perplexing, 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 2007. 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, like other estimates in this literature, our estimates reflect the cost of marginal increases in CAFE standards. They do not reflect engineering investments, capital expenditures, and other fixed costs that may be required for aggressive increases in mileage. Second, our estimates reflect compliance costs during our study period and do not necessarily hold for future years. Vehicle characteristics, consumer preferences, and technology all evolve over time. Moreover, the structure of CAFE regulation 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 an increase in the standard to 35 miles per gallon 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 impact compliance costs. Finally, our estimates do not reflect changes in consumer surplus resulting from tighter fuel-economy standards.

6 Would tightening CAFE standards increase social 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 U.S. gasoline consumption, which lowers world oil

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30Contacts 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 impacted automakers during our study period but may be an important consideration moving forward.
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 (Harrington, Parry and Walls 2007), and the elasticity response at 0.1 (Small and 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. 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 (2008) both find that consumers bear over 80% 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. Removing the standard would be better than keeping the loophole, however, as using the loophole to relax the constraint is costly.

We also calculate the implicit carbon price that would, given our cost estimates and the assumption that total private losses are five times producer losses, make increasing CAFE standards welfare neutral. The break-even carbon prices are $28–$52 (trucks) and $45–$74 (cars) per metric ton of carbon dioxide. While these prices are substantially higher than

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

(14)

\footnotetext[31]{We obtain information on average lifetime miles weighted by survival rates from the U.S. 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, \( \sigma \) 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:

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

where \( \xi \) is the elasticity of miles with respect to mileage. A negative value implies that tightening the CAFE standard yields net external benefits. Discounting at an annual rate of say 3% would reduce the magnitude of net benefits by about 20% but would not change its sign.
conventional damage estimates of roughly $15 per ton (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 Weitzman (2007) has separately concluded that taking into account structural uncertainty about the possibility of catastrophic climate change may lead to similarly 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 (e.g., National Academy of Sciences 2002, Congressional Budget Office 2003, Austin and Dinan 2005, West and Williams 2005, and Jacobsen 2008).

7 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 Corporate Average Fuel Economy (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 (Byrne 2003; Bloomberg News 2007; Shepardson 2007).

We estimate that the cost of marginally tightening CAFE standards, as revealed by profit-maximizing behavior in the auto industry, is relatively small. To do so, we demonstrate that automakers exploit an incentive or “loophole” in CAFE regulation that allows them to relax CAFE standards 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 indirectly reveal their marginal compliance costs. Based on this
approach, we estimate that tightening CAFE standards by one mile per gallon would cost
domestic automakers $8-$28 in profit per vehicle. 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 indus-
try. 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 ob-
vious, 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 car-pool lanes, zoning laws, and a variety of environmental restric-
tions, where a loophole-based methodology may prove useful. We suspect that this approach
will, at a minimum, complement other methods for estimating marginal compliance costs.

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