A Structural Analysis of Vehicle Design Responses to Corporate Average Fuel Economy Policy

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ABSTRACT
The U.S. Corporate Average Fuel Economy (CAFE) regulations, which aim to influence automaker vehicle design and pricing responses, have been imposed for thirty years, with new target regulations enacted in 2007. We present a structural analysis of automaker responses to generic CAFE policies. We depart from prior CAFE analyses by focusing on vehicle design responses in long-run oligopolistic equilibrium, and we view vehicles as differentiated products, taking demand as a general function of price and product attributes. We find that firm responses to CAFE standards follow a distinct pattern: Firms ignore CAFE when the standard is low, treat CAFE as a vehicle design constraint for moderate standards, and violate CAFE when the standard is high. The violation point depends on the penalty and the vehicle design is independent of the standard. Thus, increasing CAFE standards will eventually have no impact on vehicle design if the penalty for violation is not also increased. We implement a case study using vehicle simulation, cost models, and mixed logit demand model to examine equilibrium price and engine size decisions with a fixed vehicle body. We find that current standards are near the violation point, although numerical predictions are sensitive to vehicle assumptions. Firm responses are more sensitive to fuel prices than to CAFE standards, with the 2007 average fuel price implying that current CAFE standards are too low to affect vehicle design. A CAFE violation penalty keeping pace with inflation would create a wider CAFE effectiveness band than the current stagnant penalty.

Keywords: Corporate average fuel economy; Energy policy; Oligopolistic market; Mixed logit

1 INTRODUCTION

When people drive vehicles, they generate negative externalities that impact society; among them are congestion, national security implications and environmental impact, such as greenhouse gas (GHG) emissions that contribute to global warming (*1*). While economists generally advocate Pigovian taxes to efficiently correct for these negative externalities (*2, 3*), the vast majority of the U.S. public and lawmakers object to increased gasoline taxes (*4, 5, 6, 7*), and the government has instead relied on mandated restrictions for the average characteristics of vehicles sold by automakers. Among such policies are 1) the corporate average fuel economy (CAFE) standards in the U.S., which penalize automakers whose sales-weighted average of fleet fuel economy drops below a government-determined standard, and 2) similar policies in California and in Europe that set standards on average fleet carbon dioxide (CO_2) emissions per mile. These policies aim to create incentives for automakers to produce more efficient fleets. However, vehicle design responses to government policies are complicated by tradeoffs in available technology, consumer preferences, and competition in the marketplace. Integrated analysis is required to understand and predict vehicle design responses to transportation policies.

The CAFE standards regulate the average fuel economy of new vehicles sold in the United States. It requires the fleet-wide sales-weighted average fuel economy of automobiles sold by each manufacturer to achieve a prescribed standard. Manufacturers not reaching the CAFE standard are penalized based on their annual vehicle sales and amount of average fuel economy shortfalls. The origin of CAFE regulation can be traced back to the 1973 oil crisis when the Energy Policy and Conservation Act (EPCA) of 1975 established separate CAFE standards for passenger cars and light trucks (*8*). National Highway Traffic Safety Administration (NHTSA) has been assigned to establish, amend, enforce fuel economy standards and regulations, and determine the penalty for violating the CAFE standard. The initial penalty value set in 1978 was $5.00 per vehicle per 0.1 mpg. In 1997, NHTSA raised the penalty to $5.50 per vehicle per 0.1 mpg (*9*). However, the penalty has not been changed since then and has not been adjusted for inflation. Figure 1 shows the annual changes of CAFE standards and average vehicle fuel efficiency. Historically, only European automobile manufacturers have paid CAFE fines, while Japanese automakers have consistently exceeded the regulatory standard and U.S. automakers have treated the CAFE standard as a constraint, using the CAFE credit system when necessary to avoid paying penalties.

In 2007, Congress passed the Energy Independence and Security Act of 2007 (EISA), which increased fleet-wide average fuel economy standard to 35 mpg in 2020 while combining cars and light trucks into a single category (*10*). The legislation also requires NHTSA to annually reform the separate fuel economy standards for cars and light trucks in order to achieve the joint 2020 goal of 35 mpg. In April 2008, NHTSA initiated a proposal for the 2011-2015 CAFE standards of passenger cars and light trucks. It also pointed out that through an annual 2.1% increase for 2016-2020 (*11*). The unreformed standards are shown in the dash lines in Figure 1. Note that during the 1990s combined fuel economy decreased even as the fuel economy in the separate car and truck categories increased due to consumers switching from cars to light trucks.

Carbon dioxide (CO_2) emission standards that are measured on a fleet average per-mile basis can be seen as structurally equivalent policies to CAFE for regulating automobile fuel efficiency. The estimated CO_2 emissions per gallon of gasoline burned are roughly 8,788 grams (*12*), without including CO_2 emissions arising from the petroleum supply chain. We review the two most well-known standards, the European Union CO_2 emission standard and the California CO_2 emission standards. Figure 2 shows the CAFE and the two CO_2 emission regulatory standards over time. The European emission standard has the strictest requirement, whereas the U.S. CAFE regulation is the weakest criteria and California emission standards fall in between. However, the three regulations have similar slopes for equivalent annual fuel economy increases. The common mechanism of the three regulations is to set increasing standards for vehicle characteristics (fuel consumption or emissions) and expect automobile manufacturers to respond with revised vehicle lines and pricing strategies that achieve the standards. Nevertheless, vehicle design responses to government policies are complicated by tradeoffs in available technology, consumer preferences, and competition in the marketplace. We propose an integrated structural analysis to understand and predict vehicle design responses to transportation policies.

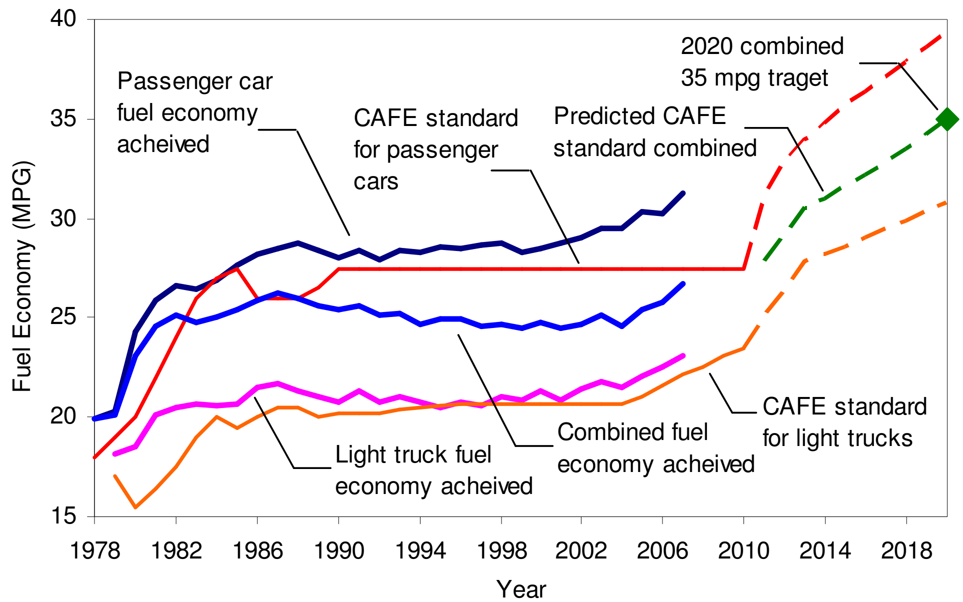

FIGURE 1 Historical and prospective changes of CAFE standards and average fuel economy records

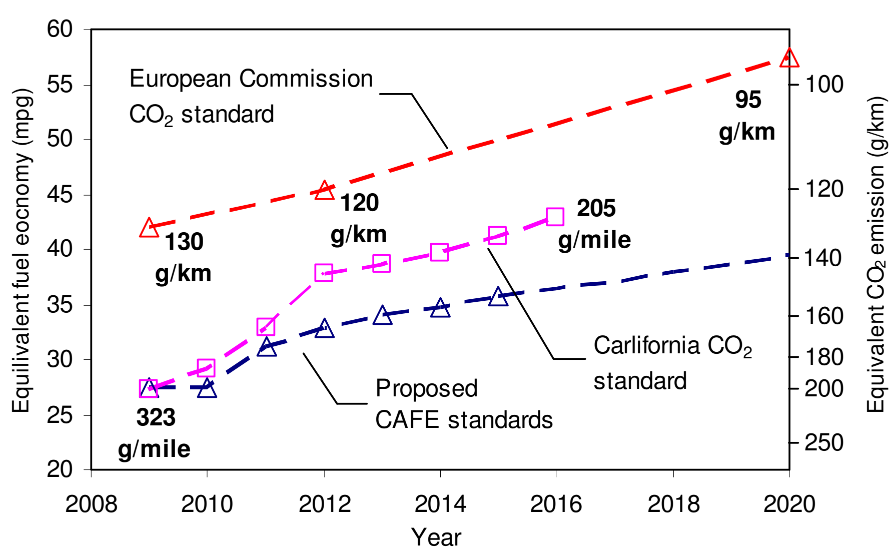

FIGURE 2 Comparisons of three fuel efficiency regulations for passenger cars

2 CAFE LITERATURE REVIEW

Studies of CAFE effects follow two primary branches: econometric estimation and economic modeling. Econometric estimation studies use automobile sales data to examine the past effectiveness of CAFE policy (*13, 14, 15, 16, 17*). In contrast, economic modeling studies draw on economic theory to simulate hypothetical manufacturer decision-making in response to CAFE or other policies with the aim to predict automaker responses to alternative regulation scenarios and understand structural policy implications. The literature on economic modeling of CAFE policy can be categorized along two major dimensions where vehicles are viewed either as commodities or as differentiated products. If firms view vehicles as commodities, they control only price or production volume, while firms with differentiated products also control vehicle design attributes, such as fuel economy or performance. If consumers view vehicles as commodities, they react only to price; however, consumers of differentiated products also react to vehicle attributes, such as fuel economy or performance. Table 1 summarizes the prior literature with respect to this categorization.

Several studies treat vehicles entirely as commodities: Kaowa (*18*) and Biller and Swann (*19*) examine a single firm, using linear models of demand and treating the CAFE standard as a constraint. The former showed that using price to shift the sales mix has a potential risk of causing increased fuel consumption with increased CAFE standards. The later showed the feasibility of manufacturers utilizing price as a short-term strategy to motivate consumers to purchase fuel efficient vehicles to achieve fleet-wide fuel economy standards. Kleit (*20*) posed a model with two vehicle commodities (small car and large car) and examined perfect competition and oligopoly models by treating the CAFE penalty as a shadow tax and taking firms as price takers or price setters, respectively. Kleit argues that CAFE policy can be not only inefficient, but also counterproductive by encouraging drivers to drive more in response to the reduced operation costs of higher fuel efficiency vehicles (the rebound effect). He argues for elimination of CAFE in favor of Pigovian gasoline taxes; however, Gerard and Lave argue that CAFE is potentially an effective complement to gasoline taxes (*21, 22*).

TABLE 1 Literature Categorization on Firm Decision and CAFE Regulation Modeling

<table>
<tr><td colspan="3"></td><td colspan="2">Demand modeling</td></tr>
<tr><td colspan="3"></td><td>Commodities
Demand as a function of price only</td><td>Differentiated
Demand as a function of price and attributes</td></tr>
<tr><td rowspan="6">Market structure</td><td rowspan="3">Commodities
No design change (Short run)</td><td>Single firm optimization</td><td>Kwoka (1983)
Biller & Swann (2006)</td><td>-</td></tr>
<tr><td>Perfect competition</td><td>Kleit (1990)</td><td>-</td></tr>
<tr><td>Oligopolistic competition</td><td>Kleit (1990)</td><td>-</td></tr>
<tr><td rowspan="3">Differentiated
Design change considered (Long run)</td><td>Industrywide optimization</td><td>-</td><td>Greene & Hopson (2003)</td></tr>
<tr><td>Perfect competition</td><td>Kleit (2004)
Fischer et al. (2007)</td><td>-</td></tr>
<tr><td>Oligopolistic competition</td><td>Austin & Dinan (2005)</td><td>Michalek et al. (2004)
This paper</td></tr>
</table>

The remaining studies view vehicles as differentiated from the manufacturer's perspective and account for long run vehicle design changes made by firms in response to CAFE policy. Using cost-technology and technology-demand models from a prior study (*23*), Greene and Hopson (*24*) constructed a nonlinear programming (NLP) framework using an industry-wide net value of fuel economy improvement as the objective function and treating the CAFE standard as a constraint. Their results showed that the vehicle lifetime fuel savings resulting from fuel efficiency improvement responses is relatively more sensitive to fuel prices than fuel economy standards. Kleit (*25*) adopted Greene and Hopson's cost-technology model to extend his previous study (*20*) to include manufacturer fuel economy responses to CAFE standard increases under perfect competition using a price-elasticity demand matrix. Kleit assumes that firms must pay for increased fuel efficiency, but changes in fuel economy do not affect demand. The study concluded that a 3.0 mpg increase in the CAFE standard can be replaced by an 11 cent gasoline tax to save the same amount of gasoline annually at only one-fourteenth of the social welfare cost.

Adopting Kleit's (2004) demand elasticity model, Austin and Dinan (*26*) modeled manufacturer pricing and fuel economy improvement decisions treating CAFE as a constraint. Their simulation predicted that an increase in the CAFE standard of 3.8 mpg will take 14 years to reduce annual gasoline consumption by 10%, while gasoline taxes are able to produce instant fuel savings. Fischer et al. (*27*) constructed a unique mathematical model of firm profit maximization with respect to vehicle fuel consumption and sales quantities given exogenous prices and treating CAFE as a constraint. They found that the efficiency and benefits of tightening CAFE standards are difficult to quantify, but they recommend that fuel economy standards should be raised gradually over time. Finally, Michalek et al. (*28*) conducted a numerical study of firm responses to CAFE standards accounting for consumer responses to vehicle fuel economy and performance as well as price. They adopted a multiattribute logit model based on past vehicle sales to model demand and a vehicle simulation model to model technical tradeoffs between fuel economy and performance. They argue that CAFE standards can result in greater fuel economy improvements at lower cost to the manufacturer; however, they do not account for government revenue generated.

The bulk of prior studies treat vehicles as commodities to consumers; however, there exists a rich literature on econometric measurement of consumer responses to (differentiated) vehicle attributes (*29, 30, 31, 32, 33, 34, 35*). We argue that vehicles are not commodities, and accounting for consumer preferences and technical capabilities is important to understanding firm responses to CAFE. As such, we view vehicle as a differentiated product from the perspective of the firm and the consumer, where firms control vehicle design variables and consumers react to vehicle attributes as well as price. We instead develop a general structural analysis of long-run oligopoly Nash responses (*36*) to CAFE policy under general assumptions for cost functions, technical tradeoffs, and consumer demand, and we identify a distinct pattern in Nash responses to CAFE. We then instantiate the model with specific data and examine policy implications.

3 PROPOSED MODEL

3.1 General Case

We define firm k's profit function as:

$$\Pi_k = \left(\sum_{j \in J_k} q_j \left(p_j - c_j \right) - c^{\mathrm{I}} \right) - \left(\rho \eta \left(z_{\mathrm{F}k}^{\mathrm{AVG}} \right) \sum_{j \in J_k} q_j \right) \tag{1}$$

where p_j, q_j and c_j are the price, demand and cost, respectively, of vehicle j; J_k is the set of vehicle models produced by firm k; c^{I} is a fixed investment cost per vehicle model; ρ is the penalty for CAFE violation in dollars per vehicle per mpg; $\eta(\cdot)$ is the CAFE violation function; and $z_{\mathrm{F}k}^{\mathrm{AVG}}$ is the CAFE achieved by firm k. According to NHTSA's CAFE formulation definition, the fleet-wide average fuel economy for manufacturer k is:

$$z_{\mathrm{F}k}^{\mathrm{AVG}} = \frac{\sum_{j \in J_k} q_j}{\sum_{j \in J_k} \frac{q_j}{z_{\mathrm{F}j}}} \tag{2}$$

The discontinuous function $\eta(z_{\mathrm{F}})$ can be expressed as:

$$\eta\left(z_{\mathrm{F}k}^{\mathrm{AVG}} \right) = \begin{cases} 0 & \text{if } z_{\mathrm{F}k}^{\mathrm{AVG}} > z^{\mathrm{S}} \quad \text{(case 1)} \\ 0 & \text{if } z_{\mathrm{F}k}^{\mathrm{AVG}} = z^{\mathrm{S}} \quad \text{(case 2)} \\ z^{\mathrm{S}} - z_{\mathrm{F}k}^{\mathrm{AVG}} & \text{if } z_{\mathrm{F}k}^{\mathrm{AVG}} < z^{\mathrm{S}} \quad \text{(case 3)} \end{cases} \tag{3}$$

We take the fuel economy $z_{\mathrm{F}j}$ and cost c_j of each vehicle j to each be a function of a vector of vehicle design variables $\mathbf{x}_j$, so that $z_{\mathrm{F}j}=f_{\mathrm{F}}(\mathbf{x}_j)$ and $c_j=f_{\mathrm{C}}(\mathbf{x}_j)$. We further take the demand q_j for each vehicle j to be a function of the design $\mathbf{x}_{j'}$ and price $p_{j'}$ of all vehicles j' in the market, so that $q_j=f_{\mathrm{Q}}(p_{j'},\mathbf{x}_{j'};\forall j' \in J)$. Finally, we assume that each firm sets the price p_j and design $\mathbf{x}_j$ of its vehicle, and the investment cost c^{I} and policy parameters z^{S} and ρ are taken as exogenous.

The three cases in Eq. (3) are classified by the relationship between fleet fuel economy design decisions and the CAFE fuel economy standard: In case 1 the fleet fuel economy surpasses the standard ($z_{\mathrm{F}}>z^{\mathrm{S}}$); in case 2 the fleet fuel economy matches the standard ($z_{\mathrm{F}}=z^{\mathrm{S}}$); and in case 3 the fleet fuel economy violates the standard ($z_{\mathrm{F}}<z^{\mathrm{S}}$). The derivative of η with respect to average fuel economy $z_{\mathrm{F}}^{\mathrm{AVG}}$ is:

$$\frac{\partial \eta}{\partial z_{\mathrm{F}k}^{\mathrm{AVG}}} = \begin{cases} 0 & \text{if } z_{\mathrm{F}k}^{\mathrm{AVG}} > z^{\mathrm{S}} \quad \text{(case 1)} \\ \text{undefined} & \text{if } z_{\mathrm{F}k}^{\mathrm{AVG}} = z^{\mathrm{S}} \quad \text{(case 2)} \\ -1 & \text{if } z_{\mathrm{F}k}^{\mathrm{AVG}} < z^{\mathrm{S}} \quad \text{(case 3)} \end{cases} \tag{4}$$

To be noticed, the function $\eta(z_{\mathrm{F}}^{\mathrm{AVG}})$ has continuity, but its derivative is discontinuous at $z^{\mathrm{AVG}}_{\mathrm{F}k}=z^{\mathrm{S}}$.

In the long-run scenario, manufacturers alter price and vehicle design under competition and CAFE policy. We consider price and vehicle design as endogenous, while the CAFE standard and penalty are applied to the competitive market as exogenous variables. We assume the market is described by Nash equilibrium, where all manufacturers compete non-cooperatively in an oligopoly market (*37*). Also, for simplicity each manufacturer is assumed to produce a single vehicle model only. We examine first order conditions (FOC) for Nash equilibrium in each of the three cases below.

Case 1. Vehicle gas mileage surpasses the CAFE standard: In this case the first order condition with respect to price p_j from Eq. (1) is:

$$\frac{\partial \Pi_k}{\partial p_j} = \frac{\partial q_j}{\partial p_j}\left(p_j - c_j\right) + q_j = 0 \tag{5}$$

Therefore, the price at market equilibrium can be expressed as:

$$p_j = c_j + q_j\left(-\frac{\partial q_j}{\partial p_j}\right)^{-1} \tag{6}$$

Here the equilibrium price is comprised of vehicle cost plus manufacturer markup, where the markup depends on total demand (itself a function of price) and the price elasticity. Assuming that the design variable space is unconstrained, the first order condition with respect to the design variables $\mathbf{x}_j$ is:

$$\frac{\partial \Pi_k}{\partial \mathbf{x}_j} = \frac{\partial q_j}{\partial \mathbf{x}_j}\left(p_j - c_j\right) - q_j\frac{\partial c_j}{\partial \mathbf{x}_j} = 0 \tag{7}$$

Inserting Eq.(6) and assuming positive demand, the equation becomes:

$$\frac{\partial q_j}{\partial \mathbf{x}_j}\left(\frac{\partial q_j}{\partial p_j}\right)^{-1} + \frac{\partial c_j}{\partial \mathbf{x}_j} = 0 \tag{8}$$

Here the equilibrium design is a balance between the marginal cost of a design change and the marginal price that can be charged for the design change without changing demand.

Case 2: Vehicle design gas mileage is equal to the CAFE standard: In this case the FOC condition for price is the same as Eq. (6). Since vehicle fuel economy equals the CAFE standard in this case, the design solution satisfies the design function:

$$f_{\mathrm{F}}\left(\mathbf{x}_j\right) = z^{\mathrm{S}} \tag{9}$$

If the design function has an inverse, then $\mathbf{x}_j = f_{\mathrm{F}}^{-1}(z^{\mathrm{S}})$.

Case 3: Vehicle design gas mileage violates the CAFE standard: In this case the first order condition with respect to price p_j is:

$$\frac{\partial \Pi_k}{\partial p_j} = \frac{\partial q_j}{\partial p_j}\left(p_j - c_j\right) + q_j - \rho\eta\left(z_{\mathrm{F}j}\right)\frac{\partial q_j}{\partial p_j} = 0 \tag{10}$$

The price solution becomes:

$$p_j = c_j + q_j\left(-\frac{\partial q_j}{\partial p_j}\right)^{-1} + \rho\eta\left(z_{\mathrm{F}j}\right) \tag{11}$$

Here the equilibrium price is comprised of vehicle cost, manufacturer markup and the CAFE penalty per vehicle. The manufacturer markup depends on demand and the price elasticity, and the CAFE penalty is passed to the consumer. The first order condition with respect to the design variable (again assuming no constraints) is $\mathbf{x}_j$:

$$\frac{\partial \Pi_k}{\partial \mathbf{x}_j} = \frac{\partial q_j}{\partial \mathbf{x}_j}\left(p_j - c_j - \rho\eta_j\right) + q_j\left(\rho\frac{\partial z_{\mathrm{F}j}}{\partial \mathbf{x}_j} - \frac{\partial c_j}{\partial \mathbf{x}_j}\right) = \mathbf{0} \tag{12}$$

Plugging in Eq. (11), the equation is simplified to:

$$\frac{\partial q_j}{\partial \mathbf{x}_j}\left(\frac{\partial q_j}{\partial p_j}\right)^{-1}+\left(\frac{\partial c_j}{\partial \mathbf{x}_j}-\rho\frac{\partial z_{\mathrm{F}j}}{\partial \mathbf{x}_j}\right)=\mathbf{0} \tag{13}$$

Here the equilibrium design is a balance between the marginal cost of a design change (due to direct cost and regulation cost) and the marginal price that can be charged for the design change without changing demand.

The FOC equations for Nash pricing and design solutions are summarized in Table 2. For each case, the fuel economy of vehicle design shows different characteristics and variable dependencies. Note that $z_{\mathrm{F}j}$ is independent of z^{S} in case 1 and case 3. For any given f_{F}, f_{C}, f_{Q}, and ρ such that $z_{\mathrm{F}j}^{***}>z_{\mathrm{F}j}^{*}$, which is the case for practical markets, at most two adjacent cases will have equilibrium conditions that are consistent with case assumptions for a given z^{S}. This is most easily seen visually. Figure 3 shows Nash vehicle fuel economy responses $z_{\mathrm{F}j}$ as a function of the CAFE standard z^{S} under a fixed penalty ρ, which forms three regions. Case 1 and case 3 are independent of z^{S}, so they appear as horizontal lines. Case 2 follows the 45° line passing through (0,0). Case 1 is valid for $z_{\mathrm{F}j}^{*}<z^{\mathrm{S}}$, and case 3 is valid for $z_{\mathrm{F}j}^{***}>z^{\mathrm{S}}$. Case 2 is valid for all z^{S} such that $\exists \mathbf{x}_j : f_{\mathrm{F}}(\mathbf{x}_j)=z^{\mathrm{S}}$. However, because case 2 is a border case for case 1 and case 3, it is not an equilibrium solution to the relaxed problem where $z_{\mathrm{F}j}$ is not restricted to z^{S}, and we consider case 2 only when the other two cases are invalid. Therefore, case 1 is valid for $z^{\mathrm{S}}<z_{\mathrm{F}j}^{*}$, case 3 is valid for $z^{\mathrm{S}}>z_{\mathrm{F}j}^{***}$, and case 2 is valid for $z_{\mathrm{F}j}^{*}\leq z^{\mathrm{S}}\leq z_{\mathrm{F}j}^{***}$. For the three regions in Figure 3, the policy implications are:

Region 1: Low CAFE standards are ineffective, and fuel economy and pricing decisions are determined by oligopolistic competition directly.
Region 2: Moderate CAFE standards result in fuel economy responses that follow the standard exactly.
Region 3: High CAFE standards result in fuel economy responses that violate the standard, and firms ignore further increases in the standard, instead transferring the regulation penalty cost to consumers in the retail price. The point of first violation and the resulting fuel economy response depends on the penalty for violation. Higher CAFE standards result in direct transfer of the CAFE penalty cost to vehicle price.

These results imply that CAFE standards and penalties for violation must be set in coordination in order to be effective: Setting too high a standard without a corresponding increase in violation penalties will result in firms ignoring further increases and passing costs on to consumers.

TABLE 2 First-order Conditions under Pure Oligopoly Market

	Condition	Case 1 $z_{\mathrm{F}}(\mathbf{x}_j) > z^{\mathrm{S}}$	Case 2 $z_{\mathrm{F}}(\mathbf{x}_j) = z^{\mathrm{S}}$	Case 3 $z_{\mathrm{F}}(\mathbf{x}_j) < z^{\mathrm{S}}$
	H	0	0	$z^{\mathrm{S}}-z_{\mathrm{F}j}$
	$\partial\eta_i/\partial z_{\mathrm{F}j}$	0	undefined	-1
General	Price	$p_j = c_j + q_j\left(-\frac{\partial q_j}{\partial p_j}\right)^{-1}$	$p_j = c_j + q_j\left(-\frac{\partial q_j}{\partial p_j}\right)^{-1}$	$p_j = c_j + q_j\left(-\frac{\partial q_j}{\partial p_j}\right)^{-1} + \rho\eta_j$
General	Design necessary condition	$\frac{\partial q_j}{\partial \mathbf{x}_j}\left(\frac{\partial q_j}{\partial p_j}\right)^{-1} + \frac{\partial c_j}{\partial \mathbf{x}_j} = \mathbf{0}$	$\mathbf{x}_j : f_{\mathrm{F}}(\mathbf{x}_j) = z^{\mathrm{S}}$	$\frac{\partial q_j}{\partial \mathbf{x}_j}\left(\frac{\partial q_j}{\partial p_j}\right)^{-1} + \left(\frac{\partial c_j}{\partial \mathbf{x}_j} - \rho\frac{\partial z_{\mathrm{F}j}}{\partial \mathbf{x}_j}\right) = \mathbf{0}$
	Fuel economy decision	$z^{*}_{\mathrm{F}j}$ depends on $f_{\mathrm{F}}, f_{\mathrm{C}}, f_{\mathrm{Q}}$	$z^{**}_{\mathrm{F}j}$ depends on z^{S}	$z^{***}_{\mathrm{F}j}$ depends on $f_{\mathrm{F}}, f_{\mathrm{C}}, f_{\mathrm{Q}}, \rho$
Mixed logit	Price necessary condition	$\int_{\boldsymbol{\beta}} s_j\left(\frac{\partial v_j}{\partial p_j}(1-s_j)(p_j-c_j)+1\right) f(\boldsymbol{\beta})d\boldsymbol{\beta} = 0$	$\int_{\boldsymbol{\beta}} s_j\left(\frac{\partial v_j}{\partial p_j}(1-s_j)(p_j-c_j)+1\right) f(\boldsymbol{\beta})d\boldsymbol{\beta} = 0$	$\int_{\boldsymbol{\beta}} s_j\left(\frac{\partial v_j}{\partial p_j}(1-s_j)(p_j-c_j-\rho\eta_j)+1\right) f(\boldsymbol{\beta})d\boldsymbol{\beta} = 0$
Mixed logit	Design necessary condition	$\int_{\boldsymbol{\beta}}\left(\frac{\partial v_j}{\partial \mathbf{z}_j}\frac{\partial \mathbf{z}_j}{\partial \mathbf{x}_j} + \frac{\partial c_j}{\partial \mathbf{x}_j}\frac{\partial v_j}{\partial p_j}\right) s_j(1-s_j) f(\boldsymbol{\beta})d\boldsymbol{\beta} = \mathbf{0}$	$f_{\mathrm{F}j}(\mathbf{x}_j) = z^{\mathrm{S}}$	$\int_{\boldsymbol{\beta}}\left(\frac{\partial v_j}{\partial \mathbf{z}_j}\frac{\partial \mathbf{z}_j}{\partial \mathbf{x}_j} + \frac{\partial v_j}{\partial p_j}\left(\frac{\partial c_j}{\partial \mathbf{x}_j} - \rho\frac{\partial z_{\mathrm{F}j}}{\partial \mathbf{x}_j}\right)\right) s_j(1-s_j) f(\boldsymbol{\beta})d\boldsymbol{\beta} = \mathbf{0}$

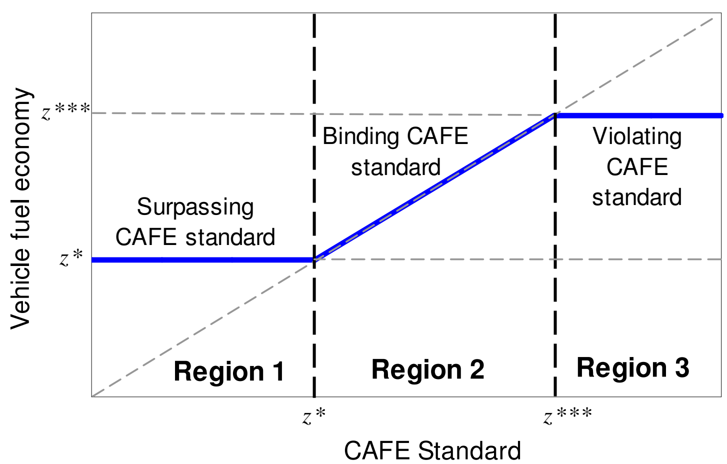

FIGURE 3 Three regions of fuel economy design responses

2.2 Logit Demand Model

To further analyze manufacturers' design response to CAFE regulations, we utilize logit model to incorporate the market demand upon consumer choices on vehicle attributes. The logit model is a random utility model, by which the utility of an individual consumer i selecting vehicle j is comprised of an observable component v_{ij} and an unobservable random error component ε_{ij}:

$$u_{ij} = v_{ij} + \varepsilon_{ij} = v_{ij}\left(\boldsymbol{\beta}_i, p_j, \mathbf{z}(\mathbf{x}_j)\right) + \varepsilon_{ij} \tag{14}$$

The observable utility is a function of vehicle price p_j, vehicle attributes $\mathbf{z}_j$ (including fuel economy), and consumer i's preference coefficients $\boldsymbol{\beta}_i$. When the unobservable random component is assumed to be an IID standard Gumbel distribution, the probability that $u_{ij}>u_{ij'}$

$\forall j' \neq j$, i.e.: the share of choices s_j or the probability that a randomly selected consumer will choose product j over the alternatives, can be simplified into an integral expression conditional on the $\boldsymbol{\beta}$ coefficients (*38*):

$$s_j = \int_{\boldsymbol{\beta}} \frac{\mathbf{exp}\left(v_{j|\boldsymbol{\beta}}\right)}{\mathbf{exp}\left(v_0\right) + \sum_{k\in K} \sum_{j'\in J_k} \mathbf{exp}\left(v_{j'|\boldsymbol{\beta}}\right)} f\left(\boldsymbol{\beta}\right) d\boldsymbol{\beta} \tag{15}$$

where $f(\boldsymbol{\beta})$ is the probability density function that describes the distribution of consumer preference coefficients over the population and v_0 is the utility of outside good. This model is called *mixed logit* or *random coefficients logit* and it can approximate any random utility model (*39*). Ignoring issues such as advertising and distribution, demand for vehicle j is defined by multiplying the market size Q (typically an exogenous parameter) with the share of choices s_j ($q_j=Qs_j$). Assuming a single-vehicle for each manufacturer and using the choice probability equations of Eq. (15), we summarize the first-order Nash conditions in Table 2, as detailed derivations are in (*40*).

4 CASE STUDY

We next examine a case study using automotive demand, cost, and design performance models from the literature.

4.1 Modeling Parameters

We adopt a mixed logit demand model from literature (*32*). The model, holding all other terms constant, poses a utility function of v_{ij} = $(\beta_{\mathrm{P}}-\exp(\beta_{\mathrm{P}\mu}+\beta_{\mathrm{P}\sigma}\varphi_{\mathrm{P}i}))p_j/\ln(\mathrm{income}_i/\$1000)$ + $(\beta_{\mathrm{C}}-\exp(\beta_{\mathrm{C}\mu}+\beta_{\mathrm{C}\sigma}\varphi_{\mathrm{F}i}))(10\gamma z_{\mathrm{F}j}^{-1})$ + $(\beta_{\mathrm{F}}-\exp(\beta_{\mathrm{A}\mu}+\beta_{\mathrm{A}\sigma}\varphi_{\mathrm{A}i}))(z_{\mathrm{A}j}/10)$ + ε_{ij}, where the β_μ and β_σ terms are the parameters of the lognormal distribution, each φ_i is a random variable with a standard normal distribution, and ε_{ij} is the IID standard Gumbel distribution. The model parameters, converted into units used here, are β_{P}=−2.86×10^{-4}, $\beta_{\mathrm{P}\mu}$=−5.999, $\beta_{\mathrm{C}\mu}$=−1.318, $\beta_{\mathrm{C}\mu}$=−0.071, β_{A}=−1.046, $\beta_{\mathrm{A}\mu}$=−0.302, and $\beta_{\mathrm{P}\sigma}=\beta_{\mathrm{C}\sigma}=\beta_{\mathrm{A}\sigma}$=0.8326. For simplicity, we assume income=\$38,000 for all i. Since no closed-form expression exists, the choice probabilities are approximated with numerical simulation using 1000 draws from the lognormal distribution, and the FOC equilibrium equations are solved using NLP methods.

We consider a midsize car body equipped with a gasoline engine as the single vehicle model. Vehicle performance is estimated using the vehicle simulator ADVISOR (*41*) with the configuration of the mid-size car body, the 95kW spark-ignition engine with power scale 0.5-2.0, and the empirical automatic 4-speed transmission module. The EPA city driving cycle (FTP) and highway driving cycle (HWFET) are tested in the simulation, and CAFE value is then calculated using the harmonic mean of 55% city and 45% highway. We fit quadratic metamodels over ADVISOR simulation data on vehicle fuel economy and acceleration as functions of the engine scaling parameter x_j: $z_{\mathrm{F}j}=a_{\mathrm{F}2}x_j^2+a_{\mathrm{F}1}x_j+a_{\mathrm{F}0}$ and $z_{\mathrm{A}j}=a_{\mathrm{A}2}x_j^2+a_{\mathrm{A}1}x_j+a_{\mathrm{A}0}$, where the coefficients for the fuel economy design function are $a_{\mathrm{F}2}$=−4.78, $a_{\mathrm{F}1}$=−23.6 and $a_{\mathrm{F}0}$=46.0 and the coefficients for the 0-30 mph acceleration time function are $a_{\mathrm{A}2}$=3.40, $a_{\mathrm{A}1}$=−11.6 and $a_{\mathrm{A}0}$=12.6. Vehicle cost is taken as linear, $c_j=b_1x_j+b_0$, with coefficients b_1=1298 and b_0=8827 (in year 2000 dollars) from (*42*). All price/cost values are in year 2000 dollars, and the figures used in the 1993 demand model are calibrated using Consumer Price Index (*43*). The average gasoline price of γ=\$1.52 per gallon at year 2000 (*44*) is considered for the base case.

4.2 Results and Discussions

The solid line in Figure 4 shows the result of the base case, which is the CAFE standard 27.5 mpg and CAFE penalty $55 per vehicle per mpg. The manufacturer's fuel economy response 27.4 mpg is near the boundary of region 2 and region 3, implying that incentives are near the point where firms have incentive to violate CAFE. This model presents a narrow window of 0.3 mpg within which CAFE is strictly binding.

Nash responses are also sensitive to the penalty for violation of the CAFE standard. We use Gross Domestic Product price index (*45*), the inflation-adjusted value for the $50 penalty in 1978 is $111 in year 2000. Clearly the current CAFE penalty $55 has lagged far below inflation. The dashed line in Figure 4 represents manufacturer design responses at a CAFE penalty of ρ=$111 per vehicle per mpg. The graph shows that the higher penalty extends the window of region 2, where CAFE is binding. The implications represent that proper selection of the penalty parameter can improve the regulation effectiveness and encourage manufacturers to treat CAFE as binding. We note that hidden costs, such as public or government relations costs, may increase the observed penalty for violation of CAFE beyond the direct financial penalty and lead to extended regions of binding CAFE standards for some firms.

Figure 5 shows a contour plot of Nash responses for a range of CAFE standard and penalty values. The interacting effect of the CAFE standard and CAFE penalty is visible: In region 1, when the CAFE standard is less than 27.1 mpg, manufacturer design responses are not affected by the CAFE standard nor penalty. In region 2, fuel economy design responses are only affected by the CAFE standard but not the CAFE penalty parameter. In region 3, fuel economy design responses are functions of the CAFE penalty but not the CAFE standard. The border between region 2 and region 3 depends on both the CAFE standard and penalty.

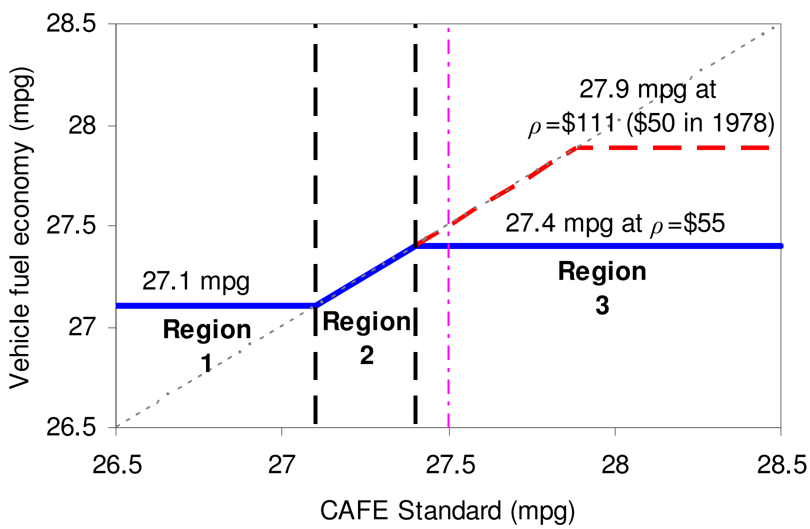

FIGURE 4 Design responses under various CAFE standards

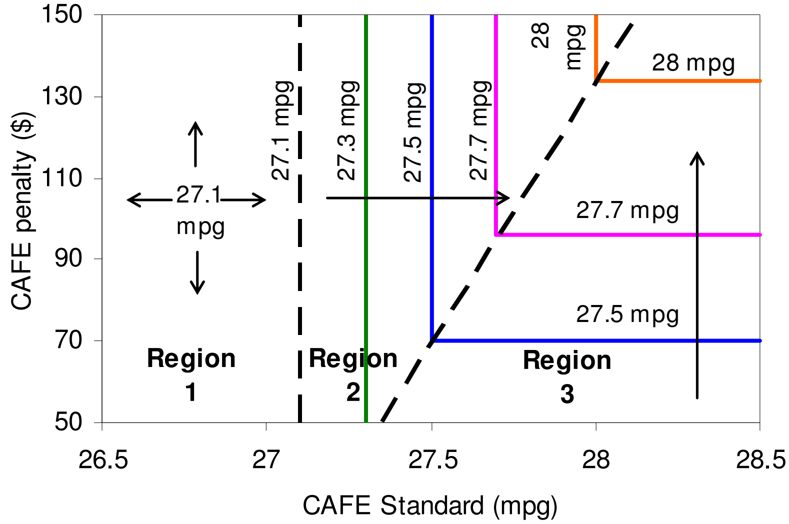

FIGURE 5 Vehicle fuel economy responses under various fuel economy standards and penalty levels

We further analyze vehicle fuel economy responses under different gasoline prices and a fixed CAFE penalty of $55 per vehicle per mpg. We use the gas price of $1.52 per gallon, the year 2000 average retail price, as the base case, and we compare it with average gasoline prices in three other years: $1.39 in 2002 ($1.33 in 2000$), $1.89 in 2004 ($1.72 in 2000$) and $2.85 in 2007 ($2.37 in 2000$) (*44*). The analysis results are shown in Figure 6. It can be seen that gasoline price variations offset the entire fuel economy response curve significantly: Increasing fuel prices shift the Nash responses upward. At high gasoline prices (e.g. the curve of $2.75 in 2007), the region 2 binding window moves up to 34-34.6 mpg, which makes the current passenger car standard 27.5 mpg less effective (region 1).

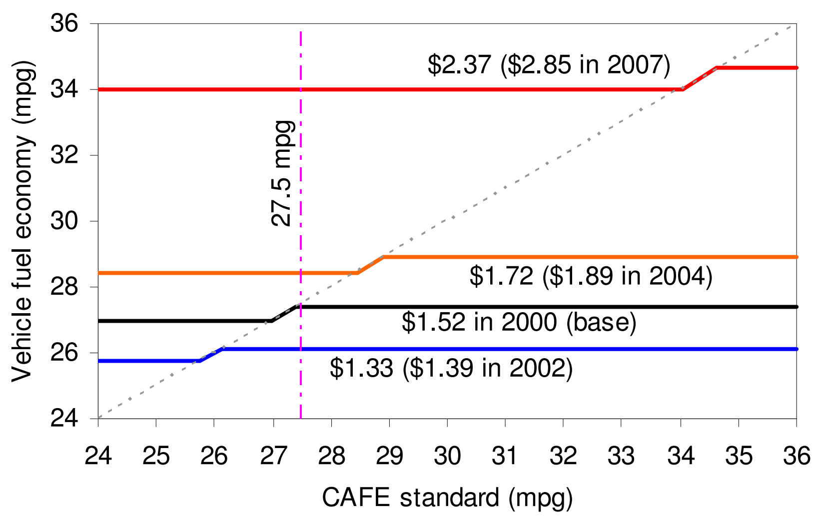

FIGURE 6 Vehicle fuel economy responses under various gasoline prices

The response curves are relatively sensitive to fuel price (because of consumer demand for low operating cost) compared to CAFE standards, despite the fact that CAFE standards more directly address fuel economy specifically (*46*). Based on this model, we find that an 8 cent increase in gasoline price ($1.60/gal) in year 2000 would result in responses of 27.5 mpg, without CAFE regulation. Thus policies that influence gasoline prices, such as fuel taxes or carbon taxes, are expected to encourage greater vehicle fuel economy improvement than adjusting the CAFE standard. Indeed, historic data on CAFE (Figure 1) shows that manufacturers have moved ahead of the CAFE standard in recent years with higher fuel prices. Furthermore, increasing fuel prices may lead CAFE policy to be irrelevant unless CAFE standards and CAFE penalties are increased accordingly: EISA set a combined car/truck CAFE target of 35 mpg (equivalent to approximately 40 mpg for cars); however, this policy may be effectively irrelevant if gasoline prices continue to rise.

5 CONCLUSIONS

We pose an oligopoly model of automaker responses to CAFE standards where vehicles are viewed as differentiated products. We find that Nash vehicle design responses to CAFE standards follow a distinctive pattern under rather general conditions: Firms ignore low CAFE standards, treat moderate CAFE standards as binding, and violate high CAFE standards, where the point and amount of violation depends on the penalty for violation. This result suggests that high CAFE standards are ineffective if penalties for violation are not also increased. While the original penalty for CAFE violation set in 1978 has not been adjusted for inflation, other factors, such as public and government relations costs for violation of CAFE standards, may contribute to extending the range of effective CAFE standards.

Our case study results show that for relatively current models of automotive demand, cost, and performance, vehicle fuel economy responses are more sensitive to fuel prices than to CAFE standards, and fuel prices address driving patterns in addition to vehicle design. This result further supports prior conclusions that view Pigovian gasoline taxes as a more efficient and effective method for reducing gasoline consumption. The effects on vehicle design caused by the increases in CAFE standards set by Congress in 2007 to 35mpg by 2020 will depend on the path of gasoline prices and the penalties set for violation of CAFE standards.

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