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Abstract

This paper presents an overview of the economics literature on the effect of Corporate Average Fuel Economy (CAFE) standards on the new vehicle market. Since 1978, CAFE has imposed fuel economy standards for cars and light trucks sold in the U.S. market. This paper reviews the history of the standards, followed by a discussion of the major upcoming changes in implementation and stringency. It describes strategies that firms can use to meet the standards and reviews the CAFE literature as it applies to the new vehicle market. The paper concludes by highlighting areas for future research in light of the upcoming changes to CAFE.

Keywords: CAFE, costs, structural estimation

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1. Introduction

The U.S. Congress first enacted Corporate Average Fuel Economy (CAFE) standards in 1975, following the 1973–1974 oil crisis. During this time, many leaders viewed the passenger vehicle sector as key to reducing the country's dependence on oil imports. The CAFE standards were created to achieve this objective by requiring new passenger vehicles sold in the United States by major automakers to reach specified minimum levels of fuel economy. Different standards applied to cars and light trucks. Figure 1 shows the trajectory of CAFE standards from 1978 to 2016.[1] After an initial phase-in period that ended in the mid-1980s, both standards remained essentially constant for nearly two decades. The standards caused fuel economy to roughly double between the mid-1970s and mid-1980s (not shown). Since then, the actual (sales-weighted) fuel economy of vehicles sold has trended down because of the increasing market share of light trucks and they fact that they are subject to a lower standard.

More than 30 years after their introduction, CAFE standards changed in 2007 and again in 2009. In 2007 they increased substantially, with legislation stipulating that over a nine-year period beginning in 2011, the standards for cars and light trucks were to increase by about 40 percent. In 2009, the Obama administration moved up the timeline for compliance from 2020 to 2016.

The implementation of CAFE also has changed, in two important ways. First, when a firm generates credits from overcomplying with the standards, it can trade the credits across the car and light truck segments, and it can trade with other firms. Second, instead of averaging fuel economy across vehicles sold within the car and light truck segments, a manufacturer will have to meet standards based on the footprint of each of its vehicles (defined by the rectangle created by its four wheels).

Coinciding with these changes has been great public interest in understanding the costs and effectiveness of using CAFE to reduce oil imports and greenhouse gas (GHG) emissions, particularly as compared to other policy tools, such as an increase in the gasoline tax or subsidizing the production and purchase of new vehicle technologies. Among regulatory policies for reducing gasoline consumption, CAFE represents a so-called command-and-control regulation. Alternatively, market-based forms of regulations, such as taxes, work via price signals (see, for example, Crandall 1992; Portney et al. 2003; Harrington and Morgenstern 2004).

[1] Fuel economy of light trucks was not regulated until model year 1978, and the standard was less stringent than the one for cars (McCarthy 2007). See Section 2.1 for further discussion of the history of CAFE.

Quantifying the costs and effectiveness of alternative policies for raising fuel economy is far from straightforward, and a full comparison requires consideration of three components. First, CAFE directly affects the new vehicle market, a market that is highly complex. A number of large firms produce many different vehicles and choose a large set of physical characteristics as well as the price of each vehicle. These features of the market present major challenges to assessing the cost of a particular technical standard to new vehicle consumers and producers.

Second, fuel economy standards for new vehicles affect the used vehicle markets. Changes in physical characteristics and prices of new vehicles affect consumers' decisions on when to retire or trade in their currently owned vehicles. Furthermore, by affecting vehicles sold in the new vehicle market, CAFE affects vehicles subsequently supplied in the used vehicle market.

Third, it is necessary to link changes in the new and used vehicle markets to the gasoline market. An increase in the CAFE standards raises the fuel economy of the fleet of vehicles in use through changes in the characteristics of new vehicles sold, but the relationship between fleet fuel economy and gasoline consumption is not one for one. An increase in fuel economy reduces the per-mile cost of driving, which may cause people to drive more and partially offset the increase in fuel economy—the *rebound effect*. Furthermore, CAFE affects the fleet of vehicles in use gradually over time, whereas many other policies, such as an increase in the gasoline tax, have more immediate effects. In short, comparing the costs and effectiveness of CAFE with those of other policies requires an analysis of many markets, firms, and consumers.

This review article discusses the literature on CAFE in the context of the major recent changes to the standards: the increases in the standards and the change to the footprint-based approach. It focuses on the first component of policy evaluation, the new vehicles market. In particular, it looks at an aspect of CAFE that has only lately received attention among economists—the effect of the regulation on firms' behavior in the new vehicles market. The economic models used to analyze the CAFE standards have grown increasingly sophisticated in an attempt to characterize many options available to firms, as well as consumer demand over vehicle characteristics and prices. One major implication of the new literature is that the cost of the CAFE standards to new vehicle producers and consumers may be substantially lower than earlier analyses found. Although a number of recent studies have investigated the new vehicle market in increasing detail, we suggest that the upcoming changes to CAFE raise a number of questions for future research on consumer and producer behavior in the new vehicle market.

Although this paper focuses on the new vehicles market, we note the treatment in the literature of the other two components of policy evaluation as well. Only a few CAFE studies have closely examined interactions between the new and used vehicle markets. Several empirical studies have estimated the magnitude of the rebound effect and have found that it offsets 10–20 percent of the reduction in fuel consumption that would otherwise occur under tighter standards (Jones 1993; Greene et al. 1999; Small and van Dender, 2007). For a more complete welfare discussion and comparison of CAFE with alternative policies, see Anderson et al. (2010); this review article discusses many of the same studies but with a greater focus on the analysis of the new vehicles market.

Finally, a number of other countries have programs similar to CAFE, but these have not been studied nearly as much as CAFE and are not considered in this paper. Many European and Asian countries use vehicle and purchase taxes, as well as fuel economy regulation, to reduce gasoline consumption. By comparison, in the United States, gasoline taxes are considered as a way to raise funds for highway construction and infrastructure maintenance. All three increases to the federal gasoline tax since 1973 were justified as a way to reduce the deficit or improve infrastructure (Sullivan 2008).

The paper proceeds with a review of the CAFE standards, including a discussion of the causes of the recent changes. Section 3 discusses the options available to firms to increase their fuel economy and presents a basic static model of the new vehicle market. We discuss the three prominent features of the market in the recent literature—imperfect competition, technological options for manufacturers, and consumer demand over vehicle price and physical characteristics. Section 4 discusses the contributions of the recent literature to characterizing all three features in a more realistic manner than did previous studies. Finally, Section 5 discusses potential areas of future research on CAFE and the new vehicles market in light of the new regime.

2. History of CAFE

2.1 CAFE I

Following the 1973 oil crisis, the U.S. Congress passed the Energy Policy and Conservation Act in 1975 with the intent of reducing oil imports. The act established the first-ever fuel economy regulations, which we refer to as CAFE I, for passenger vehicles in the United States. The National Highway Traffic and Safety Administration (NHTSA), which is part of the Department of Transportation, administers the fuel economy requirements and sets standards for other vehicle classes, such as light trucks (which include minivans, sport utility vehicles, and pickup trucks). Standards for cars and light trucks have been separate, and the light truck standards always have been lower than the ones for cars.[2] Beginning in model year

[2] See McCarthy (2007, 243) on the politics behind the lower standards for light trucks.

(MY) 1978, CAFE I required automobile manufacturers to increase the average fuel economy of cars sold in the United States from 18 miles per gallon (mpg) to 27.5 mpg by MY 1985.[3] NHTSA set fuel economy standards for light trucks starting in MY 1979 at 17.2 mpg. Both fuel economy standards rose quickly after they were introduced. Then, between the mid-1980s and the 2000s, the standards were unchanged. The light truck standards increased gradually in the 2000s, and in MY 2009 the standards were 27.5 mpg for cars and 23.1 mpg for light trucks.[4]

CAFE standards are administered on the basis of EPA's test procedure for measuring fuel economy of new vehicles.[5] Firms may also earn credits for over compliance that they can use in future years. Compliance with the standards is measured by calculating a harmonic sales-weighted average of the fuel economies of each manufacturer's product line.[6] The penalty for non-compliance was initially $5 for every 0.1 mpg below the standards, multiplied by the number of cars in the manufacturer's new car fleet that year (the penalty was increased to $5.50 in 1997). Between 1983 and 2002, total civil penalties were slightly more than $600 million, which mostly small and specialty European manufacturers paid (Yacobucci and Bamberger 2006).

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[3] The secretary of transportation has the discretion to adjust the passenger car standard within a range of 26–27.5 mpg. A decrease in the car standard to 26 mpg for the years 1986–1988 represents a temporary exemption that the secretary granted due to hardship concerns that General Motors and Ford raised at the time. (See Yacobucci and Bamberger 2006, 2.) A decrease in the light truck standard in 1980 occurred because trucks above 6,000 pounds were included in the standard for the first time that year.

[4] NHTSA has broad authority to establish the structure and targets for light trucks but not cars. NHTSA used that authority to establish light truck CAFE standards for MY 2005 to MY 2007 as well as modify the structure of the program for MY 2008 to MY 2011, which included the introduction of the attribute-based standard (Yacobucci and Bamberger 2006).

[5] NHTSA regulates CAFE standards, and the EPA measures vehicle fuel economy of each vehicle sold in the United States at its Ann Arbor, Michigan, facility. However, the fuel economy data used for compliance with CAFE do not match the fuel economy data shown on new car window stickers. The EPA has adjusted the methodology used to produce the consumer-relevant mpg data over the years to better reflect actual driving conditions. A car that achieves 35 mpg for CAFE will likely have a window sticker that has a combined (city and highway) rating of between 26 and 27 mpg (Abuelsamid 2010).

[6] Manufacturers had to meet standards separately for their domestically produced cars and for their imported cars**.** A passenger car was considered "domestic" if at least 75 percent of its content was of either United States or Canadian origin. For light trucks, the distinction between domestics and imports was in effect only from MY 1980 to MY 1996 (NHTSA 2010).

CAFE I had a large effect on the design of the American car and light truck. Figure 2 shows that cars became smaller, lighter, and powered by smaller engines.[7] In the late 1970s and early 1980s, weight and power decreased significantly as fuel economy improved. Thereafter, fuel economy remained constant while weight and power increased so that by the late 1980s, power had returned to its pre–oil-crisis level; power and weight continued to rise in the 1990s and 2000s. Similarly large changes have occurred for light trucks (not shown). Klier and Linn (2010) suggest that this pattern reflects an important initial compliance strategy for CAFE I of raising fuel economy by reducing weight and power. DeCicco (2007) and Knittel (2009) argue that nearly all the improvements to vehicle technology since that time have been used to increase power and weight without sacrificing fuel economy—that is, to maintain fuel economy at the levels of the standards.

While Figure 2 shows the overall compliance of the industry, Figure 3 shows that firms have taken different approaches regarding the level of compliance. Panel A separates the three U.S. automakers and shows that the fuel economy of their cars is quite similar to one another and the CAFE standard, particularly before the late 1990s. Panel B shows that the average fuel economy of cars sold in the United States by U.S. automakers was significantly lower than that of Honda and Toyota. The patterns for light trucks are generally similar (but not shown). Thus, historically, the U.S. automakers have just met the car standard each year, whereas Honda and Toyota have consistently exceeded it. Although it is not shown in the figure, other firms have taken yet a different approach. For example, BMW and Mercedes Benz have been consistently below the car standard and have paid the applicable fines.

2.2. CAFE II

The Energy Independence and Security Act of 2007 established stricter fuel economy standards, which we refer to as CAFE II. They begin phasing in with MY 2011, and ultimately require a combined average fuel economy of 35 mpg. The initial law required automakers to meet this level by MY 2020, but in the spring of 2009, the Obama administration changed the compliance date to MY 2016 (see Figure 1).[8]

[7] McCarthy (2007) notes that the 1970s oil price shocks and the CAFE program caused a number of changes to vehicle characteristics and technology. First, automakers eliminated about a foot of overhang, representing around 700 pounds of weight, from vehicles. Second, four- and six-cylinder engines replaced the V8-engine, which powered 76 percent of the American cars sold in the United States in 1977. Third, introducing front-wheel drive and mounting the engine cross-wise allowed automakers to reduce size and maintain cabin space by removing the hump that ran down the car's center. Finally, automakers replaced carburetors with electronic fuel injection systems, which significantly increased fuel efficiency.

[8] The final rule for CAFE became effective in May 2010. It requires the target fleet fuel economy by 2016 to be 34.1 mpg. That number is less than 35 because some reductions of GHG emissions, such as making a vehicle's air

CAFE II for the first time regulates GHGs emitted by motor vehicles, a task that EPA is authorized to oversee. As a result, EPA and the Department of Transportation jointly have set the new CAFE standards. The basis for EPA's involvement is an "endangerment finding" the agency issued in December 2009, which emanated from a Supreme Court decision in Massachusetts v. EPA. This finding states that GHG emissions from automobiles negatively affect public health and welfare: light vehicles emit 65 percent of all transportation sector GHGs, and the sector as a whole accounts for 28 percent of all U.S. GHG emissions (Yacobucci 2010).

In addition to significantly increasing the standards, CAFE II implements two changes. First, it introduces fuel economy standards based on the vehicle's footprint. Figure 4 plots the mpg standard for cars in 2016 as a function of the footprint. (Light trucks have a similar pattern to cars.) For reference, the footprint of the Toyota Prius is about 45 square feet. The figure shows that smaller cars have a significantly higher standard. The fuel economy standard for each automaker's cars and trucks is equal to the sales-weighted mean of the standard for each vehicle. For example, an automaker that primarily sells small cars would have a higher standard than an automaker that sells large cars. As a practical matter, the attribute-based standards will have different effects on different manufacturers, depending on the size mix of the vehicles they sell and how costly it will be to raise fuel economy for different sized vehicles.

The stated objective of the move to these attribute-based standards is to prevent "vehicle downsizing." The previous CAFE structure, in which all cars were held to one standard and all light trucks to another, allowed vehicle manufacturers to comply by shifting their product sales from larger to smaller vehicles within the car and light truck segments.[9] Such changes would not necessarily help the firm comply with CAFE II because smaller vehicles are subject to a higher standard. Because many car models are located in the downward sloping section of Figure 4, shifting sales toward smaller cars would raise a firm's CAFE standard and may not help it achieve compliance.

The concern over vehicle downsizing arose from the literature on vehicle safety and CAFE. Safety is an important aspect to consider when assessing CAFE's full welfare effects (see, for example, Crandall and Graham 1989; Portney et al. 2003). The existing literature has suggested that CAFE could have a quantitatively large effect on vehicle passenger safety because smaller vehicles are less safe in single-vehicle accidents, and larger vehicles pose a hazard to smaller vehicles in multiple-vehicle accidents

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conditioning system more efficient, affect the vehicle's fuel economy. If all GHG reductions would result from fuel economy improvements, the "GHG-equivalent" mileage requirement would be 35.5 mpg (Yacobucci 2010).

[9] In addition, there was an incentive to modify cars with low fuel economy so that they would be classified as light trucks and therefore subject to the lower standard.

(Gayer 2004). Jacobsen (2010b) finds that CAFE I caused about 150 fatalities per year. He estimates that CAFE II would have a much smaller effect than CAFE I on safety because of the reduction in vehicle downsizing.

The second change to the structure of CAFE is that manufacturers can trade the credits they generate by overcomplying with the standard across a firm's car and light truck fleets as well as with other firms. The motivation for allowing credit trading is to reduce the overall cost of the regulation. Introducing credit trading may also affect safety. Li (forthcoming) estimates that 12 percent of the light trucks sold in 2006 were due to the "arms race," in which consumers purchased light trucks because of safety concerns. By decreasing the safety of smaller vehicles, light trucks imposed an externality of roughly $2,000 per vehicle (insurance policies may only partially internalize this effect). It is widely believed that CAFE I caused firms to increase sales of light trucks at the expense of cars. Credit trading could reduce this practice and reduce the extent of this so-called arms race.

3. The new vehicle market and the economics of CAFE

3.1 Technical trade-offs

Because CAFE standards are sales-weighted average values of fuel economy, a firm can meet higher standards in several ways. First, a firm can change its sales mix by reducing the relative prices of vehicles with high fuel economy. Such price changes would raise the sales-weighted average fuel economy of the firm's vehicles.

In addition, a firm can change a particular vehicle model's characteristics to increase its fuel economy in the following three ways:

a) reduce the power;
b) redesign the engine or transmission to increase fuel economy without reducing power; and
c) reduce the weight.

Examples of reducing power include retuning the engine or offering a smaller engine. In contrast, a number of technologies—used jointly or alone—can raise fuel economy by a few percentage points each. For example, introducing variable valve timing or increasing the number of transmission speeds raises fuel economy. Finally, using lightweight materials or removing components decreases weight and therefore improves fuel economy.

Each option includes trade-offs. Reducing horsepower may raise fuel economy but also reduces the performance (for example, the acceleration) of the vehicle. The change in profits from this option depends on consumers' relative demand for fuel economy and performance. Increasing fuel economy by redesigning the engine or transmission raises the cost of producing the vehicle. Reducing the weight of the vehicle also is costly, in terms of either greater production costs from using lightweight materials or a decrease in consumer demand due to the removal of components the consumer finds valuable.

It is also important to distinguish the time horizon over which vehicle producers can implement changes. In the new vehicles market, the timing of firms' major decisions dictates the short, medium, and long run. Firms typically choose vehicle prices once each year, although firms also can offer price incentives during the year (the short run. Changes in vehicle characteristics typically occur every four to five years during major model redesigns (the medium run). Engine technologies change more slowly, as engines are redesigned roughly every 10 years (the long run).

Note that to improve fuel economy, a firm can change vehicle characteristics in two ways in the medium run. First, the firm can reduce vehicle weight or power. Second, the firm can modify the power train in a way that does not require the firm to redesign the engine or transmission. For example, changing from a five-speed to a six-speed transmission would increase fuel economy but would not require redesigning the transmission. Power trains are intentionally designed with this flexibility, allowing firms to respond to cost or demand shocks without having to redesign the power train.

By comparison, long-run changes include redesigning the power train—for example, by introducing hybrid technology. Compared to long-run changes, the medium-run changes are simple to implement and generally cost less, but result in smaller fuel economy gains. Referring to the list above of changes in characteristics that increase fuel economy, (a) and (c) are possible in the medium run, and (b) includes both medium-run and long-run changes. Thus, following an unexpected increase in the CAFE standards, firms may adjust prices in the short run; they may change weight, power, and modify the power train to improve fuel economy in the medium run; and they may change the power train technology in the long run.

3.2 New vehicle market—a simple model

To provide a framework for comparing the literature on CAFE and new vehicle markets, this section presents a static model of the new vehicle market. CAFE imposes a constraint on firms, requiring that the average fuel economy of their vehicles exceed a particular level. The model is used to derive first order conditions to the firm's profit maximization problem that demonstrate the incentives CAFE creates for changing vehicle prices and fuel economy.

The model has one time period, and the market contains J vehicles, indexed $j = 1...J$. Consumer demand for each vehicle depends on the price (p_j) and fuel economy (m_j) of the vehicle according to the function $q_j = q(p_j, m_j)$. The demand function includes the following assumptions: a) cross-price elasticities equal zero; b) the functional form is the same for each vehicle; and c) vehicles are differentiated only by their fuel economy. These assumptions simplify the present discussion, but the conclusions are robust to relaxing them (see Jacobsen 2010a; Klier and Linn 2010).

Each firm, indexed $i = 1...N$, sells a subset J_i of the vehicles in the market. The economics literature includes two broad categories of studies, depending on whether the firm chooses fuel economy. We assume first that fuel economy is exogenously determined for each vehicle in the market. Firms maximize profits by choosing vehicle prices, taking as exogenous the fuel economy of each vehicle, consumer demand, and the CAFE constraint. Each firm is subject to the CAFE constraint that the average fuel economy of its vehicles must meet a particular threshold, C . For simplicity, we assume that the same standard applies to all the vehicles in the market and that there is no credit trading across firms. The firm's profit maximization problem is given by:

$$\max_{\{p_j\}} \sum_{j \in J_i} (p_j - c_j) q[p_j, m_j]$$

$$s.t. \sum_{j \in J_i} q[p_j, m_j]/m_j \leq \sum_{j \in J_i} q[p_j, m_j]/C$$

where c_j is the marginal cost of producing the vehicle.[10]

Because there are no cross-price elasticities, the price chosen for one vehicle does not affect demand for other vehicles. This greatly simplifies the discussion; note that the literature often assumes that firms compete in a Bertrand-Nash manner, in which they choose prices of the vehicles they sell and take the prices of other firms as given. By comparison, in the simple case here, the firm's pricing decisions are

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[10] The constraint is commonly expressed as: $\frac{\sum_{j \in J_j} q[p_j, m_j]}{\sum_{j \in J_j} q[p_j, m_j]/m_j} \geq C$. The constraint has been rearranged to simplify the first order conditions.

that of a multiproduct monopolist, where the CAFE constraint links pricing decisions across a firm's vehicles. For example, changing the price of one vehicle affects profits from another vehicle because the price of the other vehicle may have to be adjusted to satisfy the constraint. The first-order condition for the price of vehicle j is given by:

$$\frac{p_j - c_j}{p_j} + \frac{1}{\varepsilon_j} + \lambda\left(\frac{1}{C} - \frac{1}{m_j}\right) = 0$$

where ε_j is the own-price elasticity of demand for vehicle j and λ is the multiplier on the constraint. The first two terms in the first-order condition are the standard terms for a profit-maximizing, single-product monopolist. To see the effect of CAFE on vehicle prices, suppose first that the constraint does not bind ($\lambda = 0$). The markup (the percentage by which the price exceeds the marginal cost) is inversely proportional to the negative of the own price elasticity of demand. Thus, the markup is greater for vehicles with more inelastic demand.

The final term in the first-order condition shows the effect of the CAFE constraint on vehicle prices. When the constraint binds ($\lambda > 0$), the firm reduces the price below the unconstrained vehicle price for vehicles with fuel economy greater than C. The firm raises the price above the unconstrained price for vehicles with fuel economy less than C. In other words, the firm adjusts the relative prices of its vehicles to encourage consumers to purchase more of the vehicles with high fuel economy and fewer of the vehicles with low fuel economy.

The first-order condition shows that the standard affects prices in a similar manner to a "feebate" program. Under a feebate program, the regulator chooses a target level of fuel economy. A purchaser of a new vehicle pays a fee for a vehicle with fuel economy below the target and receives a rebate for a vehicle with fuel economy above the target. By subsidizing vehicles with high fuel economy and taxing vehicles with low fuel economy, the feebate program shifts sales toward vehicles with high fuel economy and away from vehicles with low fuel economy. Although the market equilibrium may be different under the CAFE standards, CAFE and a feebate program thus push prices and quantities in the same directions.

Next, we consider the case in which the firm chooses the fuel economy of each vehicle at the same time as it chooses the price. In this case, raising fuel economy also raises the marginal cost of the vehicle, so that $c_j = c(m_j)$, with $c' > 0$. The first-order condition for vehicle price is the same as above. The first-order condition for fuel economy is:

$$(p_j - c_j)\frac{\partial q_j}{\partial m_j} - q_j \frac{\partial c_j}{\partial m_j} + \lambda\left(\frac{1}{C} - \frac{1}{m_j}\right)\frac{\partial q_j}{\partial m_j} = 0$$

Similarly to the case with exogenous fuel economy, first suppose that the CAFE constraint does not bind. The firm equates the marginal cost and marginal benefit of increasing fuel economy. The first term shows the effect on demand of increasing fuel economy; profits increase in proportion to the difference between the vehicle price and marginal costs as well as in proportion to the effect of fuel economy on demand. The second term shows that increasing fuel economy also raises costs.

The final term shows that the effect of CAFE on fuel economy for each vehicle is ambiguous and depends on the functional forms. When the constraint binds, for vehicles with fuel economy greater than C, the left-hand side of the first-order condition would be positive at the level of fuel economy and prices chosen in the preceding paragraph, in which the CAFE constraint did not bind. Under certain conditions, imposing CAFE could cause fuel economy of a firm's vehicles to diverge; the firm will increase the fuel economy of vehicles that initially have high fuel economy and decrease the fuel economy of vehicles that have low fuel economy. Under different conditions, imposing CAFE could cause firms to increase fuel economy of all vehicles.

Thus, the simple model demonstrates the effect of CAFE on vehicle prices and suggests that in general, the effect of CAFE on fuel economy is ambiguous. Allowing for endogenous fuel economy implies that the cost of CAFE to firms would be lower than if fuel economy is exogenous. However, that does not have to be the case for all firms in a more general model, particularly accounting for heterogeneity across firms. For example, suppose there are two sets of firms, domestic and foreign, and cross-price demand elasticities are positive. In the initial equilibrium, with a CAFE constraint, average fuel economy of domestic firms' vehicles exactly equals the constraint, and average fuel economy of foreign firms' vehicles exceeds the constraint. Suppose further that if fuel economy is exogenous, an increase in the standard would cause domestic firms to adjust vehicle prices to meet the new standard. This could cause consumers to substitute to foreign-made vehicles and increase their profits. By comparison, if domestic firms are able to increase the fuel economy of each vehicle when the CAFE standard increases, fewer consumers would substitute to foreign firms' vehicles, and foreign firms' profits would be lower than in the case where fuel economy is exogenous.

It is necessary to specify the demand function to estimate the cost of CAFE. Some studies of new vehicle markets use a random coefficients logit model, while many others use a nested logit model. See Berry (1994) for a general discussion of the trade-offs of using these models.

While a simple model like ours can illustrate some of the effects of CAFE on market equilibrium, it does omit a few important features of the market and the upcoming CAFE standard. First, firms may raise fuel economy by changing other vehicle characteristics, for example, by reducing weight or power. As noted above, such changes typically require an increase in production costs or a reduction in the characteristics that consumers positively value. Such margins need to be incorporated in an analysis of CAFE II.

Second, the model includes neither footprint-based standards nor credit trading. It assumes a single standard for all vehicles, but in practice a separate standard would apply for each vehicle size. According to EPA and NHTSA, one objective of using the footprint-based standards is to prevent the type of changes in the sales mix described above. The extent to which this objective will be met depends on the relative costs of raising fuel economy, the demand functions, and the trade-offs involved with changing other vehicle characteristics. The next section discusses how the literature has addressed these issues.

4. Effect of CAFE on the new vehicle market

The literature review in this section is organized by the treatment of fuel economy in the new vehicle market model. We first discuss papers that treat vehicle characteristics as exogenous, then papers that treat them as endogenous, and, finally, papers that specifically focus on CAFE II.

A common structural approach taken in the literature is to begin with a new vehicle market model that is similar to the one presented in section 3.2 but that relaxes many of the assumptions. These papers estimate demand and supply parameters, and generate welfare estimates by simulating the new equilibrium under an increase in the standards.

4.1 Exogenous vehicle characteristics

A number of papers treat vehicle characteristics as exogenous in estimating the cost of CAFE. Greene (1991) estimates the cost to firms of raising fuel economy by changing prices. The paper assumes that all costs fall on producers, and demand follows a multinomial logit structure. Greene finds that a 1 mpg increase in fuel economy costs $100–200 per vehicle for U.S. manufacturers (1985 dollars). This is somewhat higher than the level of the CAFE fine, which suggests that adjusting vehicle prices is an expensive means of complying with the standards. Although that result was obtained under a number of strong assumptions, numerous subsequent studies have confirmed it.

Goldberg (1998) and Jacobsen (2010a) take broadly similar approaches to comparing CAFE with the gasoline tax. Both studies use a joint discrete vehicle choice and continuous vehicle usage model, in which products are defined by market segment and manufacturer. Goldberg adopts a nested logit structure and further allows for heterogeneous preferences across households by including interactions between vehicle characteristics and household demographics in the estimation. The supply side is modeled as an oligopoly in which firms choose vehicle prices and import shares; marginal costs are recovered from the first-order conditions. Goldberg compares the effect on gasoline consumption of CAFE with the gasoline tax. Using 1989 as the base year, eliminating CAFE would increase gasoline consumption by about 19 million gallons, which would be offset by an increase in the gasoline tax of $0.80 per gallon.

Jacobsen (2010a) extends the analysis in several ways.[11] First, the paper allows for the fact that CAFE constrains some firms, whereas others have historically exceeded the standards, and a few have paid the fine. This complicates the estimation of marginal costs, which are estimated from markups and demand elasticities. Second, following Bento et al. (2009), the paper models vehicle choice and usage simultaneously rather than estimating these decisions separately. This approach allows for consistent welfare estimates in vehicle and gasoline markets. Third, the paper integrates the new and used vehicle markets, which allows for a more complete welfare analysis. The paper compares the effects of raising CAFE with increasing the price of gasoline. The results suggest that CAFE is several times more costly than the gasoline tax, and costs about $20 billion per year. The paper also finds that allowing for consumer heterogeneity and the presence of used vehicle markets has important implications for distributional impacts across firms and income groups.

4.2 Endogenous vehicle characteristics

Several recent papers include endogenous vehicle characteristics. When fuel economy is exogenous, vehicle price elasticities are the main parameters that need to be estimated on the demand side of the market. With endogenous fuel economy, the cost of increasing fuel economy and consumer demand for fuel economy become particularly important. Some studies assume that consumers treat discounted fuel savings equivalently to the vehicle price, other studies take estimates from the empirical literature on consumer demand for fuel economy, and a third group of studies directly estimates consumer demand. Most studies use engineering-based estimates of the relationship between production costs and fuel economy, and make some allowance for the fact that these estimates, when combined with estimated demand for fuel economy, imply that firms could increase profits by raising fuel economy.

Kleit (2004) and Austin and Dinan (2005) compare the cost-effectiveness of the gasoline tax and CAFE. On the demand side of the market, the authors obtain price elasticities from a survey of vehicle buyers undertaken by a large automaker. Both studies aggregate vehicle models to the level of market segment

[11] In addition to the extensions we discuss, the paper also estimates the welfare effects of CAFE allowing for endogenous fuel economy improvements. It does so in a manner that is similar to that in Austin and Dinan's (2005) paper, which we discuss below. Also, note that Jacobsen uses a random coefficients model instead of a nested logit model.

by manufacturer. Firms can increase fuel economy, and Kleit assumes the market is competitive, whereas Austin and Dinan model the market as an oligopoly. Also, Austin and Dinan use different assumptions for evaluating the gasoline tax. Kleit estimates the cost of a 3-mpg increase in the CAFE standards to be $2 billion per year, which is 14 times greater than the estimated cost of the gasoline tax. In contrast, Austin and Dinan estimate the cost of raising CAFE by 3.8 mpg to be about $3.6 billion, and roughly three times higher than the cost of raising the gasoline tax.

Shiau et al. (2009) analyze a differentiated product market in which firms choose prices and the vehicle design. Design choice includes engine size and technology implementation (for example, a six-cylinder engine with cylinder deactivation). The paper uses a simulation model to estimate vehicle production costs in terms of vehicle design characteristics. Demand is assumed to follow a random coefficients logit specification. With these inputs, the paper analyzes the effect of the CAFE standards on vehicle design. The authors find that at its present level, the CAFE constraint is not binding for a representative firm. Higher standards, however, would generate fuel economy improvements. Much higher standards would cause the firms to pay fines, unless the fines are also increased.

Gramlich (2010) does not directly assess the effects of CAFE on new vehicle markets but does use a model with endogenous fuel economy. The paper investigates the effect of gas prices on fuel economy, where firms trade off fuel economy against vehicle quality. Firms move along a technological possibility frontier when the gasoline price changes and select higher fuel economy and lower quality when the gasoline price is high. Gramlich estimates consumer demand for fuel economy, and accounts for endogenous quality by exploiting the fact that firms choose fuel economy before prices. The paper reports a strong consumer demand for fuel economy and concludes that a gasoline price of $4.55 per gallon would result in the same fuel economy level as CAFE II.

Klier and Linn (2010) expand the set of margins that firms can use to increase fuel economy and model firms' choices of vehicle performance, weight, and fuel economy. The analysis allows for trade-offs between power, weight, and fuel economy, as well as changes to power train technology that increase fuel economy while leaving other characteristics unchanged. Demand follows a nested logit structure, where consumers choose among models within each market segment. The paper estimates that consumers have a larger willingness to pay for power than fuel economy while accounting for the fact that firms choose these vehicle characteristics. The estimated costs of CAFE are significantly lower when allowing for the firms' choice of fuel economy.

Anderson and Sallee (forthcoming) take a much different approach to estimate the cost of CAFE. The sale of a flex-fuel vehicle (which is capable of using ethanol) generates additional CAFE credits, and the cost of offering flex fuel is typically about $100–200 per vehicle. They observe that under four conditions, firms equate this cost with the cost of other compliance margins. In that case, the flex fuel cost can be used to estimate the marginal cost of CAFE. They demonstrate that the four conditions hold: 1) domestic firms are constrained, and they use the flex fuel credits to achieve compliance; 2) flex fuel technology is installed on some but not all vehicles; 3) firms rarely exceed the credit limit allowed by law; and 4) consumers do not value the flex fuel characteristic. The authors find that the estimated cost is much lower than other studies, which do not incorporate this (or many other) margins available to firms and rely on strong assumptions regarding market structure; note that these are the estimated costs to producers, whereas the costs reported above are the total costs to producers and consumers.

Table 1 summarizes the key features of these studies. Overall, the literature has found CAFE to be significantly more costly per gallon of gasoline saved than a gasoline tax. Although direct quantitative comparisons across studies are difficult, estimates of the cost of CAFE tend to be lower when analyses include more margins of firms' decisions. It is also difficult to compare consumer demand estimates—price elasticities of demand or consumer demand for fuel economy—because the various studies use different demand models and different types of data sets (i.e., individual- or market-level data). The more recent literature has found that consumers have significant demand for fuel economy, although whether consumers treat a change in discounted fuel costs equivalently to a change in the vehicle price remains an open question (Allcott and Wozny, 2009; Busse et al., 2009; and Bento et al., 2010). In comparison to the focus on consumer demand, there has been very little recent analysis of the cost of raising fuel economy.

4.3 Analysis of CAFE II

Only a few existing studies have assessed the effects of the upcoming changes to CAFE. Knittel (2009) focuses on the technical feasibility of meeting CAFE II. Using historical model-level data on vehicle characteristics since 1980, the paper reports the estimated technical tradeoffs between power, weight and fuel economy. A 10 percent weight reduction (300 pounds for a typical car) would raise fuel economy by roughly 4 percent (1 mpg). The elasticity of fuel economy with respect to horsepower or torque is about -3 (the results differ for cars and light trucks). This suggests that it is technically feasible to meet the new CAFE standards, yet the actual power and weight increases observed in the market since 1980 would be reduced by 25 percent (see Figure 2). The conclusion that the standards are technically feasible using existing technology is consistent with the rulemaking analysis by EPA and NHTSA for CAFE II (U.S. EPA and NHTSA 2010b). However, the EPA and NHTSA analysis precludes a reduction in vehicle performance and focuses instead on changes manufacturers already use that raise fuel economy without reducing performance. Thus, although the studies similarly conclude that the upcoming standards will not require innovation, it is an open question as to which of the available strategies manufacturers will use most widely.

In addition to significantly raising the standards, the upcoming regulation also introduces credit trading. Austin and Dinan (2005) allow for credit trading but assume perfect competition in the credit market. Rubin et al. (2009) investigate the effects of imperfect competition in the credit market on the overall costs of CAFE. The paper uses a simplified structure of the vehicle market, but it models the credit market as an oligopoly with a competitive, price-taking fringe. Firms can generate excess credits by increasing the fuel economy of their vehicles. The authors find a Nash equilibrium in which each oligopolist chooses the profit-maximizing fuel economy of its vehicles, given the fuel economy of other vehicles in the market and the behavior of firms in the fringe. The authors obtain numerical solutions based on estimated costs and consumer valuation of an increase in fuel economy. The paper concludes that allowing credit trading reduces the cost of CAFE by 7–16 percent. The estimated cost is similar whether the credit market is modeled as perfectly or imperfectly competitive.

5. Conclusions

The economics literature on CAFE has focused on firms' pricing decisions, and, more recently, on the firms' choices of vehicle characteristics. Because of the interest in comparing the cost-effectiveness of CAFE with other policies, the literature has focused on incorporating the new vehicle market into a model that includes households' decisions regarding vehicle scrappage and purchases, as well as vehicle miles travelled. Because this analysis includes other markets besides new vehicles, it is necessary for computational reasons to aggregate vehicle models to the market-segment level and to limit the variables that firms can choose. Only recently has research focused more on the treatment of the new vehicles market itself.

Comparing estimates across studies is not straightforward, but studies that incorporate more margins along which firms can respond to fuel economy regulations tend to estimate lower compliance costs. However, these studies consider relatively small increases in the CAFE standards, on the order of 1–3 mpg. Furthermore, they have not yet incorporated many of the new features of CAFE II. Thus, they provide some insight into the likely effects of the new regulation, but considerable work will be needed to develop a model that captures the most important margins along which firms could respond, including changing vehicle characteristics and adopting new technology, as well as the new features of CAFE II.

By comparison, the rulemaking analysis by EPA and NHTSA focuses on technical aspects of the market, with a much more sophisticated treatment of vehicle technology than in the economics literature. The rulemaking analysis includes only a limited treatment of pricing behavior, however, and it does not model competitive interactions among firms. There is also disagreement over the appropriate parameter values relating to the cost and demand for fuel economy. Consequently, our understanding of CAFE II has the following significant gaps:

a) Firms may introduce new vehicle technologies over the next several years, but how consumers value these technologies is unclear. Far more attention should be devoted to estimating the cost of raising fuel economy in the medium and long run.
b) Some dynamic supply side decisions—including entry and exit of vehicle models, technology, learning, and uncertainty—have not been modeled in an economic framework. Linkages between the new and used vehicle markets could also receive greater study.
c) Dynamics of new vehicle purchases should be included. For example, if the CAFE standards are expected to increase, consumers who prefer large vehicles may purchase these vehicles before the increase occurs.
d) Whether interactions may occur between the product market and the CAFE credit market is unknown.
e) Generally, the footprint-based approach in CAFE II has not been incorporated into new vehicle market models.

The EPA has announced plans to raise CAFE standards further between 2017 and 2025, making these issues even more salient. Thus, the major increases in stringency and the changes in the structure of CAFE create a need for research that incorporates the demand and supply sides of the new vehicle market in a more detailed manner than was needed with static fuel economy standards, typical of CAFE I.

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Table 1

Comparison of CAFE Studies

Authors	Demand framework	Supply framework	Policy evaluation	Policy conclusions
		Panel A: Exogenous Fuel Economy		
Greene (1991)	Multinomial logit choice model across individual car model-engine combinations.	Producers incur all costs.	Estimates cost of raising fuel economy by changing vehicle prices.	Increasing fuel economy by 1 mpg costs $100–$200 per vehicle (1985 dollars).
Goldberg (1998)	Vehicle ownership and usage jointly determined. Nested logit structure with new vehicle products differentiated by market segment, manufacturer, and domestic status.	Oligopoly: firms choose vehicle prices and domestic shares. Distinguishes between firms that exceed standard and firms that pay fine.	Estimates effect on gasoline consumption of eliminating CAFE or raising gasoline tax.	Eliminating CAFE has same effect on gasoline consumption as raising gasoline tax by $0.80 per gallon.
Jacobsen (2010a)	Vehicle ownership and usage jointly determined. Random coefficients logit demand with new vehicle products differentiated by manufacturer and market segment.	Oligopoly: firms choose vehicle prices. New vehicle market linked to competitive used vehicle market. Adds constrained category of firms to Goldberg (1998).	Compares 1 mpg increase in CAFE with increase in gasoline tax.	CAFE costs ~$20 billion per year; about six times higher than gasoline tax.

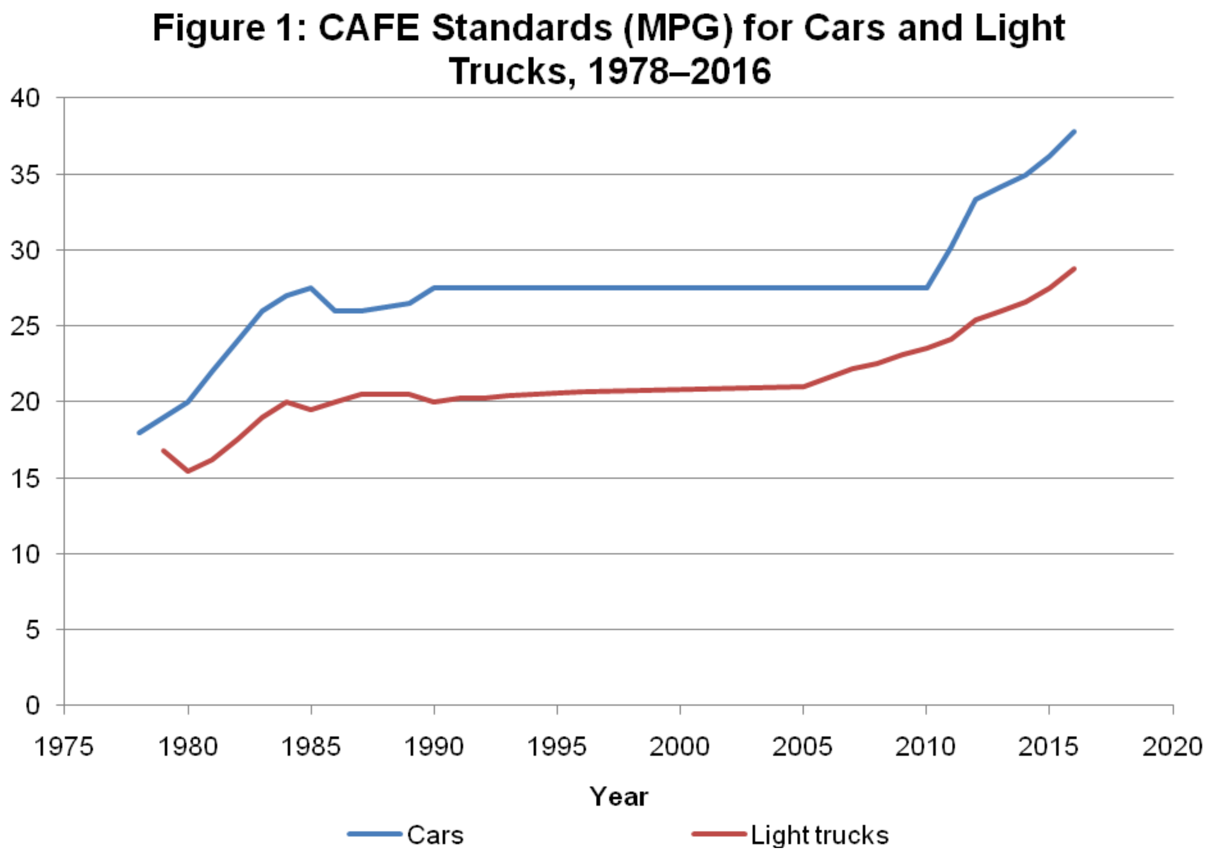
Table 1 (continued)

Authors	Demand framework	Supply framework	Policy evaluation	Policy conclusions
		Panel B: Endogenous Fuel Economy		
Kleit (2004)	Price elasticities estimated from industry data. New vehicle products differentiated by manufacturer and market segment.	Perfect competition.	Compares 3 mpg increase in CAFE with increase in gasoline tax that reduces gasoline consumption by same amount.	Total cost of CAFE to new vehicle market: $2 billion per year (1999 dollars); 14 times more expensive, per gallon saved, than gasoline tax.
Austin and Dinan (2005)	Same demand structure as Kleit.	Oligopoly: firms choose prices and fuel economy.	Similar to Kleit, comparing 3.8 mpg increase in CAFE with increase in gasoline tax.	Total cost of CAFE: $3.6 billion per year (without trading); three times more costly than gasoline tax.
Shiau et al. (2009)	Random coefficients logit model with new vehicle products differentiated by model.	Single-product oligopolist chooses price and vehicle design.	Considers effect on vehicle price and design for different levels of CAFE standard.	CAFE not binding at current level; firms raise fuel economy at intermediate level and pay fine at high level.
Klier and Linn (2010)	Nested logit structure with new vehicle products differentiated by model.	Oligopoly: firms choose prices, fuel economy, weight, and power.	Estimates cost of 1 mpg increase in standards.	Total cost of CAFE: $13 billion per year.

Table 1 (continued)

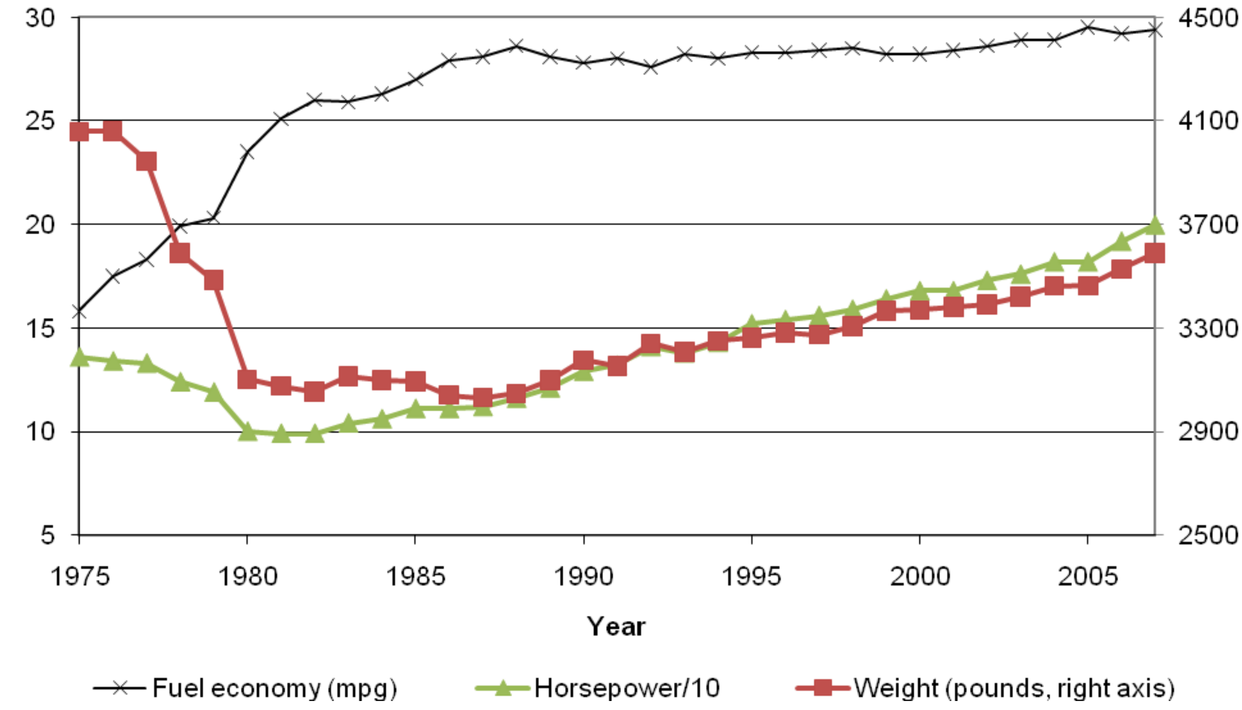
Anderson and Sallee (2010)		Firms can use flexible fuel credits to comply with standards. Marginal cost of alternative compliance options equals marginal cost of credits.	Estimates marginal cost of CAFE to producers.	Marginal cost of $8–$18 per vehicle (total cost to producers less than $300 million per year).

Notes: Each row describes a paper that is discussed in the text. The first column outlines the demand side of the model, and the second column outlines the supply side. The final two columns describe the policy evaluations and conclusions.



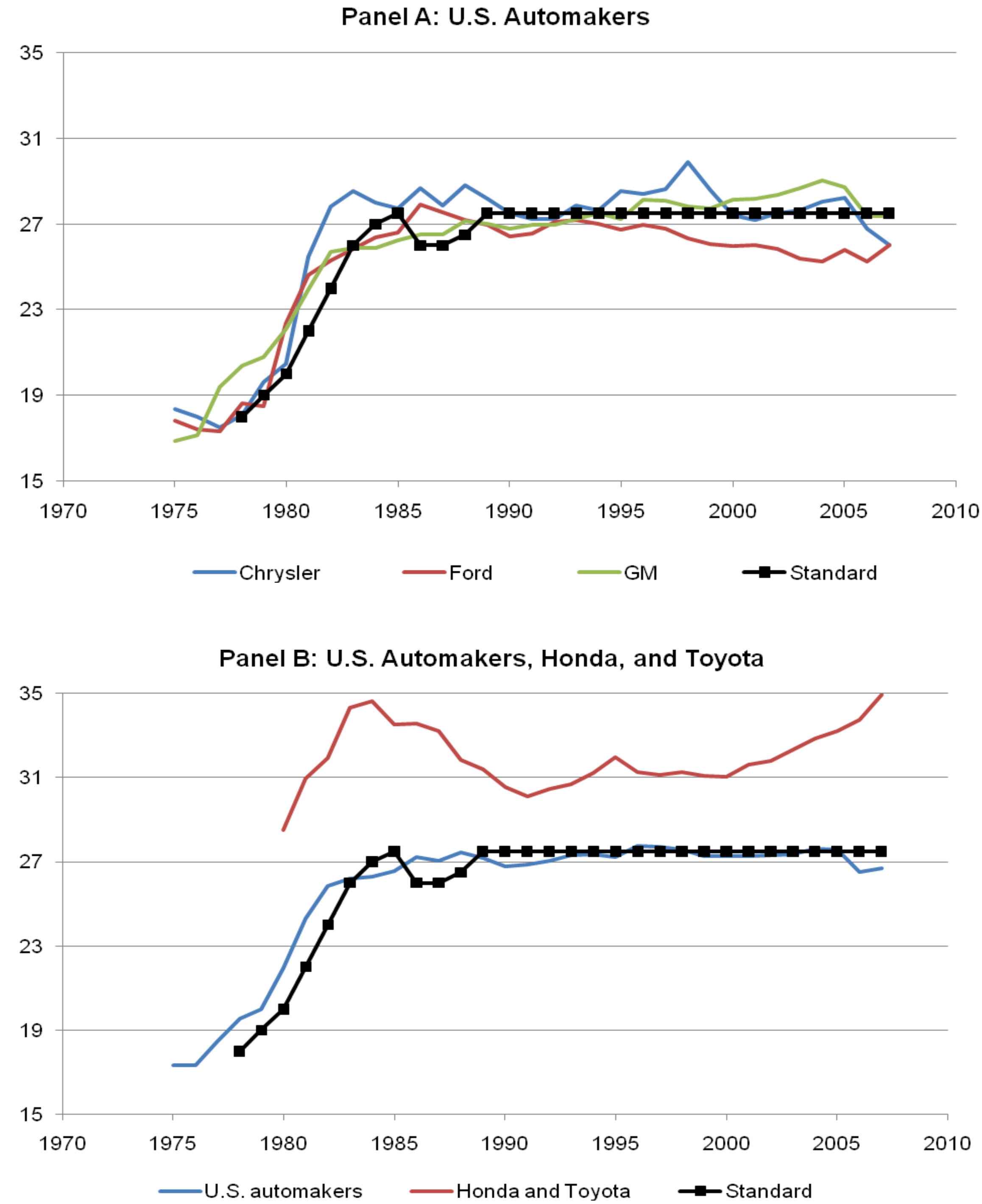
Notes: Figure is constructed from data in NHTSA (2010).

Figure 2: Fuel Economy, Weight, and Power of Cars, 1975–2007



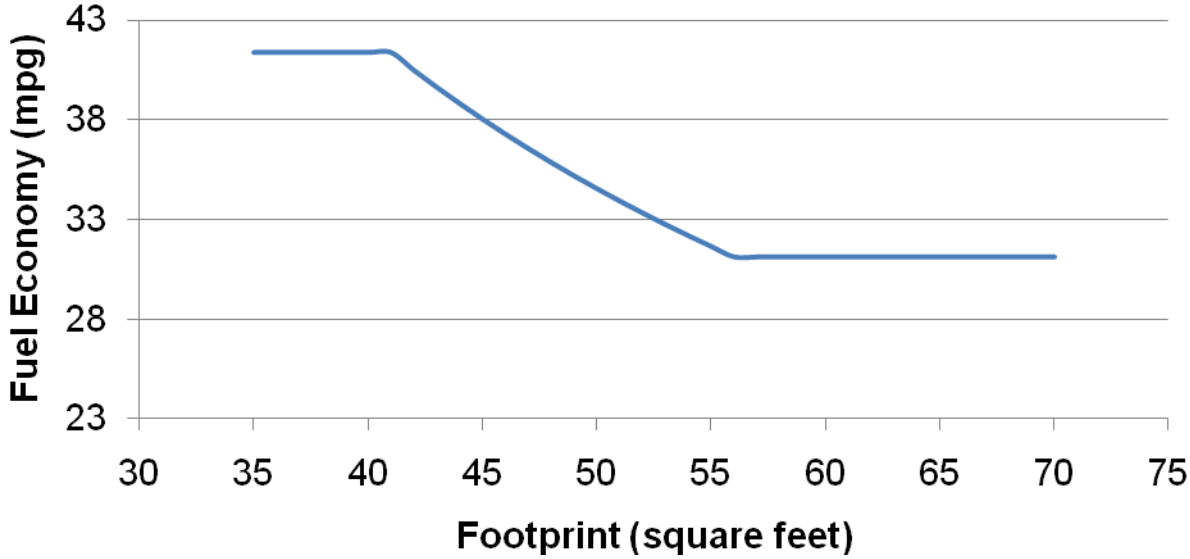
Notes: Figure is constructed using data reported in U.S. EPA (2007)

Figure 3: Mean Fuel Economy (MPG) of Cars for Selected Firms, 1975–2007



Notes: Figure is constructed using data from Ward's Auto and NHTSA (2010). Fuel economy does not reflect the use of flex-fuel credits. Sales data for Honda and Toyota are not available prior to 1980.

Figure 4: Fuel Economy Standard versus Footprint for Cars in 2016



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