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Design incentives to increase vehicle size created from the U.S. footprint-based fuel economy standards

Kate S. Whitefoot [a,*], Steven J. Skerlos [a,b]

[a] Design Science, University of Michigan, Ann Arbor, MI, United States
[b] Mechanical Engineering, University of Michigan, Ann Arbor, MI, United States

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ABSTRACT

The recently amended U.S. Corporate Average Fuel Economy (CAFE) standards determine fuel-economy targets based on the footprint (wheelbase by track width) of vehicles such that larger vehicles have lower fuel-economy targets. This paper considers whether these standards create an incentive for firms to increase vehicle size by presenting an oligopolistic-equilibrium model in which automotive firms can modify vehicle dimensions, implement fuel-saving technology features, and trade off acceleration performance and fuel economy. Wide ranges of scenarios for consumer preferences are considered. Results suggest that the footprint-based CAFE standards create an incentive to increase vehicle size except when consumer preference for vehicle size is near its lower bound and preference for acceleration is near its upper bound. In all other simulations, the sales-weighted average vehicle size increases by 2–32%, undermining gains in fuel economy by 1–4 mpg (0.6–1.7 km/L). Carbon-dioxide emissions from these vehicles are 5–15% higher as a result (4.69×10^{11}–5.17×10^{11} kg for one year of produced vehicles compared to 4.47×10^{11} kg with no size changes), which is equivalent to adding 3–10 coal-fired power plants to the electricity grid each year. Furthermore, results suggest that the incentive is larger for light trucks than for passenger cars, which could increase traffic safety risks.

1. Introduction

In order to reduce the greenhouse gas emissions and oil consumption associated with passenger transportation, the U.S. Congress recently amended fuel economy regulations on new passenger vehicles in the form of the Corporate Average Fuel Economy (CAFE) standards. Responding to criticisms that CAFE encourages the production of smaller vehicles, which unfavorably impacts domestic automakers compared to foreign automakers and may also increase traffic safety risks, the CAFE regulations for vehicles produced from 2011 to 2016 are a function of the footprint (wheelbase by track width) of the vehicles in a manufacturer's fleet such that manufacturers that produce larger vehicles can meet lower fuel economy standards. This regulation design could potentially create an incentive for automotive manufacturers to increase the size of their vehicles and diminish the policy's goal of reduced fuel consumption. Understanding this issue is both important and timely; policymakers are currently developing the CAFE regulations for vehicles produced from 2017 to 2025 and are planning to finalize these regulations by July 2012.

Given these footprint-based standards, a profit-maximizing manufacturer will evaluate various tradeoffs to determine whether modifying vehicle footprint is desirable. These tradeoffs include the marginal reduction in the fuel economy standard, the cost of modifying vehicle footprint, the impact on vehicle fuel economy and other aspects of vehicle performance such as acceleration, and the resulting change in consumer demand. Therefore, any design incentives to modify vehicle footprint will depend on the relationships between these factors.

The National Highway Traffic Safety Administration (NHTSA) states that the dependency of fuel economy targets on vehicle footprint was established such that any incentive to increase or decrease vehicle size would be minimized (NHTSA, 2009). However, despite researchers' recommendations for further investigation (NRC, 2002; Greene and Hopson, 2003), no quantitative analysis was performed to assess what effect the chosen standards have on design incentives to increase or decrease vehicle size. The most closely related analysis examines the impact of weight-based fuel economy standards on changes to vehicle weight (Greene and Hopson, 2003). But, because the relationships between vehicle weight and consumer demand, production costs, fuel economy, and other vehicle attributes are not necessarily the same as the analogous relationships for footprint, their results cannot directly be applied to footprint-based standards.

This study uses simulation analysis to test the hypothesis that the footprint-based CAFE standards will not create an incentive to

* Corresponding author. National Academy of Engineering, USA. Tel.: +1 202 334 1643.
E-mail addresses: kwhitefoot@nae.edu (K.S. Whitefoot), skerlos@umich.edu (S.J. Skerlos).

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increase vehicle size. An oligopolistic equilibrium model of the U.S. automotive industry is constructed to study firm incentives in response to the footprint-based CAFE. In this model, firms can adjust vehicle prices, tradeoff acceleration performance with fuel economy, implement fuel-saving technology features, and increase vehicle footprint. The relationships between vehicle performance attributes are determined from engineering vehicle simulations. Results are presented over a wide range of assumptions of consumer preferences for vehicle size, price, acceleration performance, and fuel efficiency.

Changes in the footprint of vehicles have implications for both fuel economy goals and traffic safety. If vehicle footprint increases, gains in fuel economy could be significantly lower. We investigate this issue by determining the change in the sales-weighted average fuel economy observed in simulations that allow firms to increase the footprints of vehicles and comparing this with fuel economy gains assuming, as in NHTSA's (2009) analysis, that vehicle size and sales remain unaffected. With respect to traffic safety, both the absolute measures of vehicle size (the dimensions of the vehicle) and the relative measures of vehicle size (spread of dimensions across vehicles) can impact safety risks (Kahane, 1997; NRC, 2002). This study investigates the impact of footprint-based CAFE standards on both the absolute change in vehicle size and relative differences in vehicle size changes between passenger cars and light trucks, which can be used in conjunction with traffic safety studies to understand the impact of footprint-based CAFE on traffic safety risks.

2. State of the art: CAFE and vehicle footprint or weight incentives

Although researchers have discussed potential design incentives induced by CAFE standards based on vehicle attributes (i.e., vehicle footprint or weight), the majority of these studies are based on qualitative reasoning rather than a quantitative analysis of firm incentives. The National Research Council (NRC) conducted an analysis of CAFE suggesting that the regulations could avoid design incentives to reduce vehicle size or weight by allowing the fuel economy standards to depend on such attributes. Specifically, the analysis reasons that proportionate weight-based fuel economy targets would eliminate motivation for weight reductions, therefore avoiding any adverse safety implications (NRC 2002, see also dissent to this conclusion in Greene and Keller, 2002). The study also mentions that these targets could cause vehicle weight to increase and lead to higher fuel consumption. These conclusions were largely based on regressions of vehicle curb weight on fuel economy and qualitative observations of vehicle weight trends. Additional studies have also raised concerns that attribute-based fuel economy standards could be susceptible to unintended incentives for firms to design vehicles to be larger or heavier in order to qualify for a less stringent standard (Norman, 1994; Greene et al., 2005).

NHTSA constructed the footprint-based CAFE standards using a quantitative analysis but did not study whether manufacturers would have an incentive to change vehicle size as a result of the standards. Fuel economy targets were defined by determining the cost-effective fuel economy that could be obtained without modifying vehicle footprints, and then by fitting a function to these fuel economy values as a function of vehicle footprint (NHTSA, 2006). NHTSA reasoned that, under footprint-based CAFE, if manufacturers redesign a vehicle model to have a smaller footprint, the manufacturer's average fuel economy would increase but so would their required average fuel economy target and, therefore, any incentive to change vehicle footprint would be reduced (NHTSA, 2005, 2006).

Greene and Hopson (2003) analyze the impact of weight-based standards on incentives to increase vehicle weight. In the study, the authors recognize that although manufacturers may be able to lower their required fuel economy standard by increasing vehicle weight, fuel economy also decreases with increased weight. They determine that increasing vehicle weight by 1% would reduce fuel economy performance by 0.6%. Assuming that increasing vehicle weight by 1% would reduce the CAFE requirement by 1% and given a combined standard of 32.7 mpg by 2015, the authors find that the weight-based standard will cause an average increase in weight by 1% and a loss of fuel economy gains by 2.5%.

In addition to studying the footprint-based standards instead of weight-based standards, our approach differs in a few other important ways from Greene and Hopson's analysis. First, we consider the ability of firms to make tradeoffs between fuel economy and acceleration performance and shift production among their vehicle models by modifying prices. This is in addition to changing vehicle footprint and implementing technology features that improve fuel economy at some added cost. Second, we model the automotive industry at a detailed scale, representing all vehicle models and engine options produced in a year by the top twenty firms that sell vehicles in the United States.

3. Methodology

To investigate potential design incentives from the footprint-based CAFE standards, we consider the decisions that an automotive manufacturer may make in response to the regulation. If a manufacturer wishes to increase the footprint of a particular vehicle, the weight of a vehicle will increase to some extent. This will negatively impact both the fuel economy of the vehicle and the acceleration performance. These losses can be alleviated by incorporating various technology features (e.g., lower friction engine components, cylinder deactivation, or lightweight materials) at some additional cost. Another option is to redesign the powertrain to improve fuel economy by compromising acceleration performance, or vice versa. A profit-maximizing manufacturer would balance these decisions based on how the resulting vehicle attributes affect vehicle sales (q), production costs (c), and the ability to meet the CAFE standard. This study is the first analysis of attribute-based standards to consider each of these tradeoffs together.

These decisions can be formulated as an optimization problem where the firm f maximizes profits subject to the constraints of the CAFE regulation. The firm can choose the footprint (ftp), acceleration performance (acc), level of additional technology features ($tech$), and price (p) of each vehicle in their fleet. The constraint of the CAFE regulation is a function of individual vehicle fuel economy targets (T), which depend on the footprint of the vehicle:

$$\max_{ftp_j, acc_j, tech_j, p_j \forall j} \sum_j q_j(p_j, mpg_j, acc_j, tech_j, ftp_j)(p_j - c_j(acc_j, tech_j, ftp_j))$$

subject to

$$\frac{\sum_{j \in \mathfrak{I}_{f,L}} q_j(p_j)}{\left(\sum_{j \in \mathfrak{I}_{f,L}} q_j(p_j)\right)/mpg_j} \geq \frac{\sum_{j \in \mathfrak{I}_{f,L}} q_j(p_j)}{\left(\sum_{j \in \mathfrak{I}_{f,L}} q_j(p_j)\right)/T_j} \tag{1}$$

where $mpg_j = f(acc_j, tech_j, ftp_j)$; $T_j = g(ftp_j)$

Because fuel economy, acceleration performance, and the types of technology features incorporated into the vehicle are all related, the above formulation considers fuel economy as dependent on the decision variables acc and $tech$. This choice is arbitrary and equivalent to the manufacturer choosing fuel economy and acceleration performance with the tech variable determined as a function of those attributes.

Demand for a particular vehicle, q_j, in Eq. (1) is dependent upon attributes of the vehicle j as well as the attributes of all

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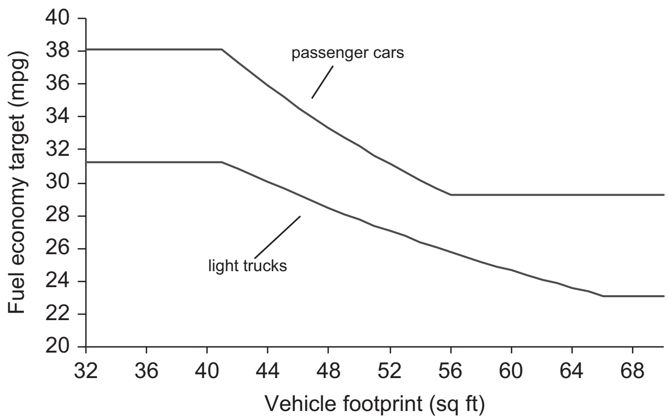

Fig. 1. MY-2014 CAFE footprint-based fuel economy targets.

other vehicles available to consumers. We account for this relationship by solving an oligopolistic equilibrium model where automotive manufacturers seek to maximize profits according to Eq. (1). The subsections below detail how each of the remaining functions in Eq. (1) are derived and how the equilibrium model is formulated.

3.1. Fuel economy targets

The reformed CAFE standards are calculated for each manufacturer as a function of the footprints of the vehicles it produces. Specifically, the regulation sets individual fuel economy targets for each vehicle based on the vehicle's footprint, where larger vehicles have lower targets. A firm will comply with the reformed CAFE standards if the sales-weighted average fuel economy of both its fleets of passenger cars and light trucks are equal to or greater than the respective sales-weighted average targets set for these vehicles as in

$$Stand_L = \frac{\sum_{j \in \Im_{f,L}} q_j}{(\sum_{j \in \Im_{f,L}} q_j)/T_j} \tag{2}$$

The variables $q_j$and T_j in this equation are respectively the sales and fuel economy target for vehicle j in vehicle class L (i.e., passenger cars or light trucks), where the set of vehicles in class L produced by firm f is denoted $\Im_{f,L}$. The model-year (MY) 2014 fuel-economy targets for passenger cars and light trucks as a function of vehicle footprint are described by Eq. (3) and illustrated in Fig. 1:

$$\begin{aligned}
&\text{passenger cars}: T_j = \\
&\quad 1/min\left(max\left(5.308 \times 10^{-4} \times ftp_j + 4.498 \times 10^{-3}, 1/38.08\right), 1/29.22\right) \\
&\text{light trucks}: T_j = \\
&\quad 1/min\left(max\left(4.546 \times 10^{-4} \times ftp_j + 1.331 \times 10^{-2}, 1/31{,}30\right), 1/23{,}09\right)
\end{aligned} \tag{3}$$

3.2. Tradeoffs between fuel economy, footprint, and acceleration performance

Increasing vehicle footprint leads to a reduction in fuel economy and acceleration performance of the vehicle due to the increase in vehicle weight. We derive these relationships by determining how vehicle weight changes with vehicle footprint and then by determining the relationship between vehicle weight, fuel economy, and 0–60 mph acceleration time. According to Stodolski et al. (1995), approximately 42% of a vehicle's curbweight is attributable to components that are not affected by increases in external vehicle dimensions, such as the engine, transmission, seats, and wheels (also see Kelkar et al., 2001). An additional 9.5% of a vehicle's weight can be approximated as independent of footprint because the height of the vehicle is unaffected.[1] Therefore, a 10% increase in a vehicle's footprint would result in approximately a 5% increase in curbweight. Sensitivity tests of this assumption are described in the Results section.

A regression analysis of the relationship between vehicle footprint and curbweight using MY2006 vehicle data was also performed to compare to this assumption. The estimates of these regression results indicate that, controlling for both engine size and vehicle height, curbweight increases 0.53% with every 1% increase in footprint. Further information on this regression is provided in Appendix A.

The relationship between vehicle weight, fuel efficiency (in gal per 100 mi), and 0–60 mph acceleration time was determined from a combination of physics-based vehicle simulations and data on technology features (e.g., cylinder deactivation). The technology features considered were derived from a subset of technologies identified by NHTSA, which are used to conduct analyses informing the CAFE rulemaking. Table 1 displays a list of the technology features considered in our simulations. The costs of these technology features, estimated by NHTSA (2008), are based on confidential data provided by automotive manufacturers, suppliers, and consultants.

The software package AVL Cruise was used together with these data to simulate the 0–60 mph acceleration time and fuel economy of several vehicle types with varying curbweights, powertrain variables (engine displacement size and the final drive ratio in the transmission), and technology features. Vehicle simulations were conducted for seven separate vehicle segments (i.e. compact cars, minivans, etc.). A total of 29,747 vehicle simulations were conducted to determine how fuel economy and 0–60 mph (0–97 kph) acceleration time change in response to small changes in vehicle curbweight and input powertrain variables. Using these simulation results, the variable tech was created by ordering the cost-effective combinations of technology features that increasingly improve fuel economy and then by assigning an integer value to each ordered combination. This variable represents a continuous approximation of the discrete choices of implementing technology features and is necessary for model tractability. The function **f** in Eq. (1), which describes the relationship between fuel economy, 0–60 acceleration performance, and the level of technology features (tech), was then fit to the simulation data. Further details about this process and the regression can be found in Whitefoot et al. (2011).

Validation tests were performed comparing the approximated relationships based on the simulation data with observed data, shown in Fig. 2. This data includes all non-hybrid vehicle models and engine options in MY-2006. Predicted fuel economy values fit the observed data with an R-squared value of 0.80.

In addition to reducing fuel economy and acceleration performance due to increases in vehicle weight, increasing vehicle footprint may also impact these attributes due to changes in the aerodynamic drag of the vehicle. However, vehicle simulations indicate that a 10% increase in vehicle footprint leads to less than

[1] The body in white, interior less seats, and window glass makes up 35% of vehicle curbweight (Stodolski et al., 1995; Kelkar et al., 2001). We assume that each of these components can be broken down into subcomponents that scale with one side of the vehicle body. Approximating a vehicle as a block with height h, length l, and width w, the surface area of the vehicle body is $2wl+2wh+2lh$. If the footprint increases by 1% the vehicle body's surface area increases by $2.02wl+2\sqrt{1.01}wh+2\sqrt{1.01}lh$. Using model-year 2006 vehicle dimensions, this represents a 0.73% increase in surface area. Therefore, we assume $(0.35)(0.27)=9.5\%$ of a vehicle's curbweight depends on the vehicle's height but is independent of the vehicle's footprint.

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Table 1
Incremental costs of technology features considered based on NHTSA's (2008) analysis.

Technology costs	Two seater	Compact	Midsize/ minivan	Fullsize	SUV	Small pickup	Large pickup/van
Low friction lubricants ($)	3	3	3	3	3	3	3
Engine friction reduction ($)	126	84	126	126	126	126	168
Aggressive shift logic ($)	38	38	38	38	38	38	38
Early torque converter lockup ($)	30	30	30	30	30	30	30
High efficiency alternator ($)	145	145	145	145	145	145	145
Aerodynamic drag reduction ($)	38	38	38	38	38	38	38
Low rolling resistance tires ($)	6	6	6	6	6	6	6
Cylinder deactivation ($)	n/a	n/a	203	203	203	203	229

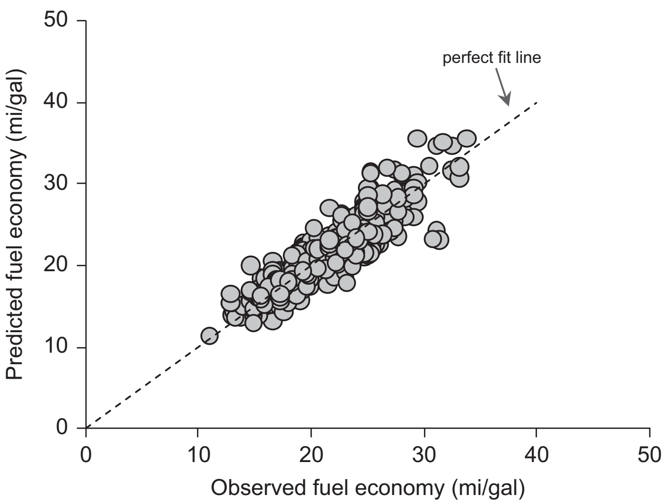

Fig. 2. Comparison of vehicle performance model to MY-2006 vehicle data.

a 1% change in fuel economy and 0–60 mph acceleration time. Therefore, aerodynamic drag is not considered in this study.

The effect of firms using light-weight materials for vehicle components where it is cost-effective under the unreformed CAFE standards are implicitly included in the vehicle performance model. The analysis does not consider the ability of manufacturers to further lightweight their vehicles. NHTSA's (2008) analysis indicate that additional lightweighting is more cost-effective, in terms of fuel-consumption reductions per additional cost, than either engine friction reduction or high-efficiency alternators, but less cost-effective than all other technology features considered. Our results indicate that manufacturers do not implement engine friction reduction or use high-efficiency alternators in the majority of vehicles (60–99% of sales depending on demand parameters), implying that lightweighting is not cost-effective for these vehicles. Therefore, we do not expect the omission of additional lightweighting to substantially affect results. Supposing the contrary, that lightweighting is more cost-effective, then firms would be able to increase the footprint of their vehicles with smaller losses in acceleration performance and fuel economy. Consequently, the extent to which firms have an incentive to increase the size of their vehicles would be, if anything, larger than the results presented in this study. However, the reduction in fuel economy gains may be lower because lightweighting lowers the relative fuel-economy penalty for increasing vehicle size.

3.3. Tradeoffs between footprint and production costs

The product development process for a vehicle model begins with a set of targets specifying vehicle design features, including target vehicle dimensions, followed by detailed design of all vehicle subsystems and ending with vehicle production (Sörenson, 2006; Weber, 2009). The choice of target dimensions at the beginning of this process impacts the resulting production costs of each vehicle in the model line. Most notably, the material costs of the body panels, chassis, glass, driveshaft, axles, and certain interior components will increase with vehicle footprint. Production costs associated with manufacturing processes may also increase. The typical vehicle assembly process involves forming steel sheets into body panels using a series of stamping operations, assembling the panels using robotic arms, spot welding the panels together, and installing subsystem components (Braess and Seiffert, 2005). The costs of these production processes may increase with the vehicle footprint, for example if more time or energy is needed to lift heavier body panels or to provide additional spot welds to assemble the larger panels. Labor costs may also increase if more time is needed to perform assembly operations, for example if additional fasteners are necessary to attach larger subcomponents to the vehicle body.

Acquiring data on these production costs as a function of vehicle footprint is difficult, but we can approximate an upper bound of the impact of increasing vehicle footprint on production costs. Because the aim of this study is to test whether an incentive to increase vehicle size exists, and the extent of this incentive, we use an upper-bound estimate of costs so that our results represent the lower bound of changes to vehicle size. As a conservative upper bound, we assume that increasing vehicle footprint will increase the incremental production costs linearly according to a 1-to-1 relationship, implying that a 1% change in vehicle footprint increases incremental production costs by 1%. We expect that many of the costs of vehicle components and manufacturing operations increase at a smaller rate with vehicle footprint—such as the material costs of body panels—or are completely independent of footprint—such as the costs associated with the seats. Therefore, we expect that this 1-to-1 assumption represents a highly conservative estimate of the impact of vehicle footprint on production costs. If the costs of increasing vehicle footprint are smaller than the assumed relationship, the incentive to increase vehicle size would be larger than results suggest.

Because targets for vehicle dimensions are set early in the product development process and subsequent design of vehicle subsystems considers these dimensions, we do not expect fixed costs associated with vehicle design to increase with incremental decisions on vehicle footprint. We also assume that fixed costs associated with manufacturing processes do not increase with decisions on vehicle footprint. One exception is that the dies used for body-panel stamping scale with footprint dimensions, and therefore the costs associated with the die material increase with footprint. However, the portion of die costs that depend on body panel area is small (Clark and Fujimoto, 1991; McGee, 1973) and so this issue is not considered here.

3.4. Consumer preferences for vehicle size, fuel economy, and acceleration

Consumer demand for new vehicles is modeled as a discrete-choice utility model where consumer utility is a function of vehicle price, fuel consumption, acceleration performance, and vehicle size:

$$U_{nj} = \alpha_1 p_j + \alpha_2 eff_j + \alpha_3 acc_j + \alpha_4 size_j + \xi_j + \epsilon_{nj} \tag{4}$$

Vehicle price, p, in Eq. (4) is measured in ten thousands of 2011 dollars. Fuel efficiency, *eff*, is measured in terms of the gallons of fuel needed to drive 100 miles, and acc is the inverse of the time to accelerate from 0–60 mph (0–97 kph) in tenths of a second, which is approximately proportional to the ratio of horsepower to vehicle weight but also depends on transmission parameters other than horsepower (e.g., the final drive ratio). The parameter size represents the overall length of a vehicle multiplied by the width (L103 by W105 according to SAE International (2005) standards) in ten thousands of sq in. Conversions between footprint and size assume that overall width minus track width, and overall length minus wheelbase, are constant. The ξ_j parameter represents the mean combined utility for all other vehicle attributes, and ϵ_{nj} is an error term specific to individual n and vehicle j.

Multiple confounding factors in observed vehicle and consumer choice data present significant challenges to accurately estimating the α demand parameters. Vehicle prices and observed attributes—including fuel consumption, acceleration performance, and size—are correlated with unobserved vehicle attributes that consumers value, such as exterior and interior styling. This correlation produces biased estimates of the demand parameters. Researchers commonly address this problem by conducting an instrumental variable regression to recover unbiased estimates of the parameters, relying on a set of instruments that are correlated with the observed attributes but are independent of unobserved attributes (e.g., Berry, 1994). However, most of these studies are only concerned with estimating the price parameter; identifying valid instruments for all the attributes listed in Eq. (4) in addition to vehicle prices is particularly challenging (Nevo, 2000). As a result, with only one exception (Klier and Linn, 2008), analyses of CAFE and alternative fuel-economy incentives that estimate consumer preferences have assumed that vehicle attributes other than fuel economy cannot change (e.g., Goldberg, 1998; Jacobsen, 2010; Austin and Dinan, 2005). Therefore, instead of attempting to solve this problem as it would apply to this study, we take a different approach, simulating multiple combinations of values for these preference parameters as scenarios that span the range of reasonably expected consumer preferences as determined by existing literature. While, in many cases, we cannot be certain that these estimates are not biased because of the confounding factors described above, the ranges of estimates in the literature are large enough to presume that they contain the set of plausible values.

Although simulating combinations of demand parameters allows us to investigate the potential incentive to increase vehicle size over multiple scenarios of consumer preferences, this enumeration of demand parameter combinations presents a challenge with regard to computational time. In order to tractably simulate a significant number of combinations of the parameters in Eq. (4), it is necessary to make a simplifying assumption that the α coefficients are common across all consumers, meaning that heterogeneous preferences are not accounted for in this model. Following customary assumptions of the logit model, the ϵ_{nj} parameters are assumed independently and identically distributed across vehicles according to a Type 1 extreme value distribution. This assumption allows the expected value of sales of vehicle j to be written as in

$$\mathbb{E}(s_j) = N \frac{e^{V_j}}{e^{V_{og}} + \sum_{k \in \Im} e^{V_k}} \tag{5}$$

$$V_j = \alpha_1 p_j + \alpha_2 gpm_j + \alpha_3 acc_j + \alpha_4 size_j + \xi_j$$

The parameter N in Eq. (5) is the number of consumers, $\Im$ is the set of vehicles in the market including vehicle j, and V_{og} is the utility of the outside good, representing the utility of not purchasing a new vehicle. Given the sales of vehicle $j(s_j)$; the number of consumers that did not purchase a new vehicle (s_{og}); and values of the α coefficients for price, fuel consumption, acceleration performance, and size, the mean utility of all other vehicle attributes (ξ_j) can be inferred as

$$\xi_j = \log\left(\frac{s_j}{I}\right) - \log\left(\frac{s_{og}}{I}\right) - (\alpha_1 p_j + \alpha_2 gpm_j + \alpha_3 acc_j + \alpha_4 size_j) \tag{6}$$

The ranges of plausible values for the α coefficients in the equations above were determined based on key properties of consumer demand for new automobiles estimated in the literature. Ranges for the price coefficient were based on estimated values for the average price-elasticity of demand, which range from -2.0 to -3.1 in the literature (Berry et al., 1995; Goldberg, 1998; Jacobsen, 2010; Klier and Linn, 2008; Train and Winston, 2007). Ranges of values for the remaining coefficients were informed based on the willingness of consumers to pay for improved fuel consumption, faster acceleration performance, and larger size as estimated from the literature. These estimates were either derived from logit models that consider consumer preferences to be homogeneous or random-coefficient logit models where the mean of the distribution is used to derive willingness-to-pay.[2] The average estimated willingness to pay for vehicle attributes ranges from \$340 to \$2000 for an additional sq ft of vehicle size (\$366–\$2150 per 1000 cm^2), \$160–\$5500 for an increase of 0.01 hp/lb in acceleration performance (\$97–\$3345 per 0.01 kW/kg), and \$1100–\$9000 for a reduction in fuel consumption of 1 gal per 100 miles (\$468–\$3826 per L/100 km) (Beresteanu and Li, 2008; Greene and Liu, 1987; Klier and Linn, 2008).

Helfand and Wolverton (2009) recently conducted a survey of consumer valuation for fuel economy and found that estimates for consumers willingness to pay for 1 mpg (0.43 km/L) more of fuel economy ranges from approximately \$200–\$600 in the literature. Using the vehicle data input into our simulations, this corresponds to an average willingness to pay as low as \$800 for improved fuel efficiency of 1 fewer gal per 100 miles (\$340 per L/100 km), which is less than the lower bound determined above. Therefore, we use \$800-\$9000 for 1 fewer gal per 100 miles (\$340–\$3826 per L/100 km) as the range of consumer preference for fuel efficiency instead.

Table 2 reports the ranges of willingness-to-pay for vehicle attributes as estimated in the literature and the α coefficients that correspond to these ranges. Ideally, combinations of these parameters for the simulations would be determined by sampling from their joint distribution. However, existing literature has neither produced estimates of this joint distribution nor characterized correlations between these parameters. Consequently, combinations of these parameters were simulated assuming independence of preference parameters so as to span the complete range of consumer preference scenarios that would be produced using any correlation of parameters. Specifically, the parameter ranges were divided up into three levels for each parameter—representing the lower bound, midpoint, and upper bound for each parameter—and combinations of these parameter levels were used as simulation inputs. Assuming that the incentive to change vehicle size is monotonic with consumer preferences for vehicle size, price, fuel efficiency, and acceleration performance, the range of the results of this study bound the

[2] Boyd and Mellman (1980), referenced in Greene and Liu's (1987) review, estimate a random-coefficient utility model using a lognormal distribution on the coefficient of fuel efficiency. In this case, the median of the distribution was used to derive willingness-to-pay values.

Table 2
Ranges of demand parameters in literature and corresponding model coefficients.

	Range of mean price elasticity		
	Low	Mid	High
Price	2.0	2.6	3.1
Corresponding coefficients, α_{price}	0.65	0.83	1.00
	Range of estimated willingness to pay		
	Low	Mid	High
Vehicle Size (sq ft)	\$340	\$1170	\$2000
(sq m)	\$366	\$1259	\$2153
Corresponding coefficient			
$\alpha_{price}=1.00$	2.12	7.44	12.71
$\alpha_{price}=0.83$	1.76	6.18	10.55
$\alpha_{price}=0.65$	1.38	4.84	8.26
Acceleration performance (0.01 hp/lb)	\$160	\$2830	\$5500
(0.01 kW/kg)	\$97	\$1721	\$3345
Corresponding coefficient			
$\alpha_{price}=1.00$	0.06	1.07	2.07
$\alpha_{price}=0.83$	0.05	0.89	1.72
$\alpha_{price}=0.65$	0.04	0.70	1.35
Fuel efficiency (gal/100 mi)	\$800	\$4900	\$9000
(L/100 km)	\$340	\$2083	\$3826
Corresponding coefficient			
$\alpha_{price}=1.00$	0.07	0.44	0.80
$\alpha_{price}=0.83$	0.06	0.37	0.66
$\alpha_{price}=0.65$	0.05	0.29	0.52

results that would be produced using any combination of demand parameters in the ranges specified. Strong evidence supporting this monotonicity is shown in the Results section.

3.5. Equilibrium model

Producer decisions regarding vehicle prices and attributes are modeled as an oligopolistic equilibrium model where firms maximize profits with respect to the prices, acceleration performance, and levels of technology features of their vehicles. The top twenty automotive firms that sell vehicles in the United States are represented in the model. Vehicles are represented as all vehicle models and engine options produced by these firms based on MY-2006 data, totaling 473 vehicles.

Firms are differentiated as to whether they are expected to meet the CAFE standards even if it is more profitable to violate them. The model allows BMW, Jaguar, Mercedes-Benz, Porsche, and VW to violate the standard and pay the legally required penalties. The profit maximization formulation for these firms takes the form of

$$\max_{ftp_j, acc_j, tech_j, p_j \forall j} \sum_j q_j(p_j - c_j) - F_C - F_T \tag{7}$$

where

$$mpg_j = f(acc_j, tech_j, ftp_j)$$

$$F_C = \left(\sum_{m \in \mathfrak{C}_C} q_m\right)\left(\sum_{m \in \mathfrak{C}_C} \frac{q_m}{q_m/T_m} - \sum_{m \in \mathfrak{C}_C} \frac{q_m}{q_m/mpg_m}\right)$$

$$F_T = \left(\sum_{n \in \mathfrak{C}_T} q_n\right)\left(\sum_{n \in \mathfrak{C}_T} \frac{q_n}{q_n/T_n} - \sum_{n \in \mathfrak{C}_T} \frac{q_n}{q_n/mpg_n}\right)$$

The parameters F_C and F_T are, respectively, the penalties for violating the fuel economy standard for passenger cars ($Stand_C$) and light trucks ($Stand_T$). Fuel economy targets, T_m and T_n, for these vehicle classes are determined by Eq. (2). All other firms are treated as constrained to the CAFE standards so that their profit maximization problems take the form of Eq. (3).

Firm decisions on vehicle footprint are constrained to a maximum of a 10% increase. This constraint is imposed to avoid extrapolation outside of the boundaries of the data used to construct the engineering performance model and to account for any potential manufacturing constraints of dramatically increasing vehicle footprint. Data of vehicle models from 1997–2010 indicate that increases in vehicle footprint by 10% compared to the previous model design occur (Chrome Systems, Inc., 2008), suggesting that any potential constraints on footprint are at least 10% and, therefore, imposing this constraint on the model causes the results to represent a lower bound with respect to the incentive to increase vehicle size under the footprint-based CAFE standards.

4. Results

Simulations were performed for a number of combinations of consumer preference parameters and the change in the sales-weighted average of overall vehicle size (length by width) across all vehicle models was determined. Table 3 presents results for scenarios in which the average price-elasticity of demand is high. This represents a conservative case in which incentives to increase vehicle size are lower because consumers are not as willing to pay for the cost of increasing vehicle size. The upper left corner of this table represents the lower bound of changes in vehicle size caused by the MY-2014 footprint-based CAFE standards. The table also illustrates how changes in vehicle size vary with different levels of consumer preferences for vehicle size, fuel efficiency, and acceleration performance.

For the results in Table 3, consumer preference parameters for acceleration performance and fuel efficiency are set at the same level (i.e., either both low, both high, or both at midpoints). Additional simulation results are presented in Table 4. These results illustrate the sensitivity of changes in vehicle size under footprint-based CAFE to consumer preference parameters, including independent variations of preference for fuel efficiency and acceleration performance. The last

Table 3
Changes in sales-weighted average vehicle size given combinations of consumer preference parameters with price sensitivity at the upper bound.

				Preference for vehicle size		
				Low	Mid	High
Preference for fuel efficiency	High	Preference for acceleration	High	−1.4 sq ft (−0.13 sq m)	+3.8 sq ft (+0.35 sq m)	+7.0 sq ft (+0.65 sq m)
	Mid		Mid	+1.5 sq ft (+0.14 sq m)	+7.5 sq ft (−0.70 sq m)	+9.2 sq ft (+0.85 sq m)
	Low		Low	+2.1 sq ft (+0.20 sq m)	+9.6 sq ft (+0.89 sq m)	+13.4 sq ft (+1.24 sq m)

Table 4
Sensitivity of results to variations in consumer preference parameters.

Price sensitivity	**Preference for fuel efficiency**	**Preference for acceleration**	**Preference for vehicle size**	**Sales-weighted average change in footprint**	
High	Mid	High	Mid	+4.0 sq ft	(+0.37 sq m)
High	Mid	Low	Mid	+9.4 sq ft	(+0.87 sq m)
High	High	Mid	Mid	+5.9 sq ft	(+0.55 sq m)
High	Low	Mid	Mid	+9.2 sq ft	(+0.85 sq m)
Mid	Mid	Mid	Mid	+10.5 sq ft	(+0.98 sq m)
Low	Mid	Mid	Mid	+11.3 sq ft	(+1.05 sq m)
High	Low	High	Mid	+5.9 sq ft	(+0.55 sq m)
High	High	Low	Mid	+9.3 sq ft	(+0.86 sq m)
High	Mid	High	Low	−1.0 sq ft	(−0.09 sq m)
High	High	Mid	Low	+1.3 sq ft	(+0.12 sq m)
Mid	Mid	Mid	Low	+4.2 sq ft	(+0.39 sq m)
Low	Low	Low	High	+16.1 sq ft	(+1.50 sq m)

line of Table 4 represents the upper bound of changes in vehicle size caused by the MY-2014 footprint-based CAFE standards.

Results indicate that there is an incentive to increase vehicle size in all simulations except the scenarios in which consumer preference for size is at the lower bound ($340 per sq ft) and preference for acceleration performance is at the upper bound ($5500 per 0.01 hp/lb). In those cases, firms have an incentive to shift production of their vehicles such that the average vehicle size decreases by 1.0–1.4 sq ft (0.09–0.13 sq m) due to low consumer preference for vehicle size compared to acceleration performance. In all other simulations, firms have an incentive to increase the size of vehicles sold, both by increasing the footprint of vehicle models and by shifting production toward larger vehicles. The incentive varies substantially depending on consumer preferences, from an average of 1.4–16.1 sq ft (0.13–1.21 sq m). This compares with an average increase in size of 1 sq ft (0.09 sq m) between 2008 and 2011.

Depending on the scenario, between 7% and 33% of vehicle models and engine options are actively constrained by the 10% upper bound on the increase in vehicle footprint. The larger percentage occurs in scenarios where consumer preference for vehicle size is high and preferences for acceleration performance and fuel efficiency are low. This suggests that the increase in vehicle size for these scenarios would be even higher if this constraint was relaxed.

Sensitivity of these results with respect to assumptions on vehicle weight and production costs was also investigated. Vehicle curbweight was assumed to increase by 0.5% for every 1% increase in footprint. A 40% variation in the percentage of vehicle weight that changes with footprint leads to less than a 5% change in results. Production costs were assumed to increase 1% for every 1% increase in footprint as a highly conservative upper bound. Assuming instead that an increase in footprint by 1% increases production costs by 0.8%, the change in average vehicle size is approximately 9% greater.

To test the impact of the incentive to increase vehicle size on fuel economy, we compare simulation results to the average fuel economy that the CAFE standards would require if vehicle size and sales remain unaffected. Specifically, the sales and vehicle footprint using MY-2006 data was input into Eqs. (1) and (2) to determine these fuel economy standards. This is similar to the process NHTSA has used to predict future levels of fuel economy, except they have used product development plans provided by automotive firms to extrapolate future vehicle attributes. Our calculations from this procedure indicate that the required average fuel economy under the MY-2014 footprint-based standards is 30.7 mpg (13.1 km/L). This is similar to NHTSA's estimated value of 31.5 mpg (13.4 km/L). Simulation results indicate that the combination of increases in vehicle size and shifts in production to larger vehicles can reduce these fuel economy requirements. The resulting required fuel economy standards from the simulations are 1.4–4.1 mpg (0.6–1.7 km/L) lower than if vehicle sales and size remained unaffected.

Simulations results also suggest that the incentive to increase vehicle size is significantly different for light trucks and for passenger cars. Fig. 3 illustrates the change in vehicle footprint and fuel economy from simulation results using midpoint values of consumer preference for fuel efficiency, acceleration performance, and vehicle size. Initial vehicle data is displayed in gray with counterfactual simulation results in black. The sizes of the circles in the figure are proportional with vehicle sales. The sales-weighted harmonic mean of fuel economy and vehicle footprint are plotted as a cross (+).

The figure illustrates that vehicle footprint increases for both passenger cars and light trucks, but that the increase in footprint

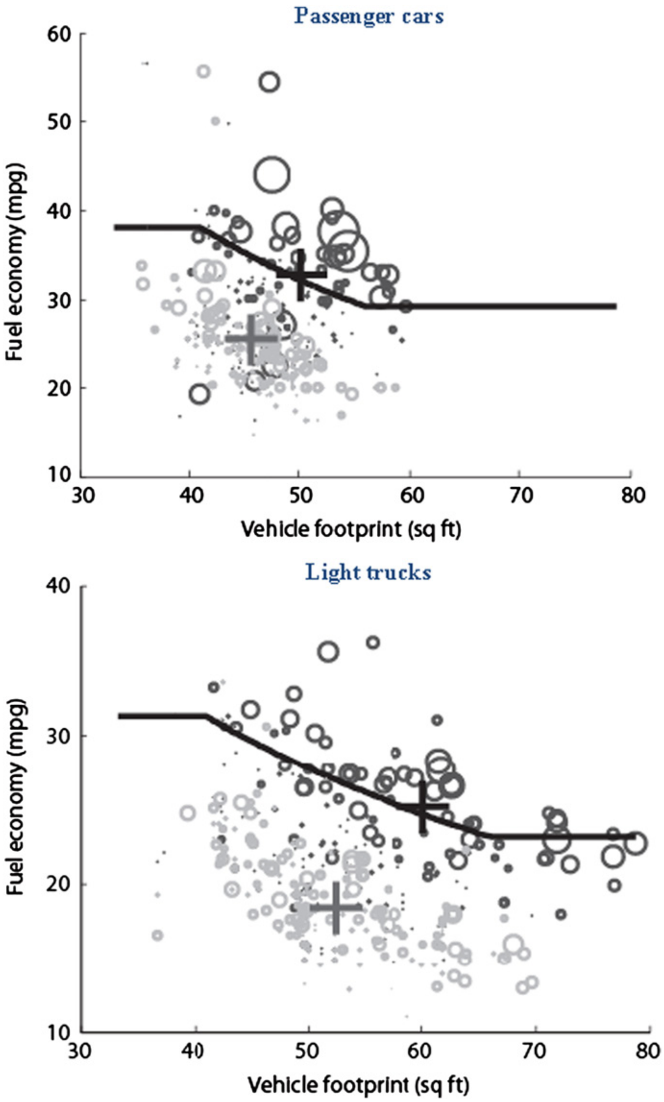

Fig. 3. Simulation results given midpoint consumer preferences. Sales-weighted harmonic mean vehicle attributes are represented as a cross (+). Initial data are in light gray, with MY-2014 CAFE counterfactual simulation results in dark gray. Circle size is proportional to vehicle sales.

for light trucks is significantly larger than for passenger cars. The sales-weighted average increase in vehicle footprint is 9.9 sq ft (0.92 sq m) for light trucks but 5.7 sq ft (0.53 sq m) for passenger cars.

This behavior can be explained by the larger impact of the CAFE standard for light trucks on firm profits than the standard for passenger cars. Simulation results give the Lagrange multiplier to the constraints in eq. (3), which is interpreted as the incremental profit loss given an incremental increase in the CAFE standard, referred to as the shadow cost of the standard. Results indicate that this shadow cost is 1.5–7.0 times larger for light trucks than passenger cars. Because the light truck standard causes larger profit losses than the passenger car standard, firms increase the sales-weighted average footprint of light trucks more than passenger cars in 20 out of the 21 simulations conducted.

Similar counterfactual simulations for the reformed CAFE standards have not been performed; so these shadow costs cannot be compared to other estimates in the literature. With regard to the unreformed CAFE standards, Anderson and Sallee (2009) also found that the ranges of estimated shadow costs of the standard for light trucks were larger than for passenger cars for Ford, GM, and Chrysler. Jacobsen (2010) found that the shadow cost for light trucks was larger than passenger cars for Ford, but that the shadow cost for light trucks was lower than for passenger cars for GM and Chrysler.

The incentive to increase vehicle size also varies substantially among vehicle models within the same class. For the case illustrated in Fig. 3, in which consumer preferences for vehicle size, fuel efficiency, and acceleration performance are all at their mid-points and price-elasticity for demand is high, increases in vehicle footprint range up to 13.8 sq ft (1.28 sq m) for certain light-truck models, and 10.4 sq ft (0.97 sq m) for certain passenger-car models. Even in the cases in which the sales-weighted average vehicle size decreases, the size of certain vehicle models increase by as much as 8.5 sq ft (0.79 sq m).

Additional simulations were performed to test the impact of changing the slope of the functions determining fuel-economy targets dependent on vehicle footprint, as described by eq. (3). These functions were iteratively modified to decrease the slopes until simulation results show no increase in the sales-weighted average footprint for the case where consumer preferences for vehicle size, fuel efficiency, and acceleration performance are all at their midpoints. Results indicate that if the slope of the function for passenger cars is reduced by a third and the slope of the function for light trucks is reduced by half, then the sales-weighted average footprint does not increase for this scenario of consumer preferences. Fig. 4 illustrates these results.

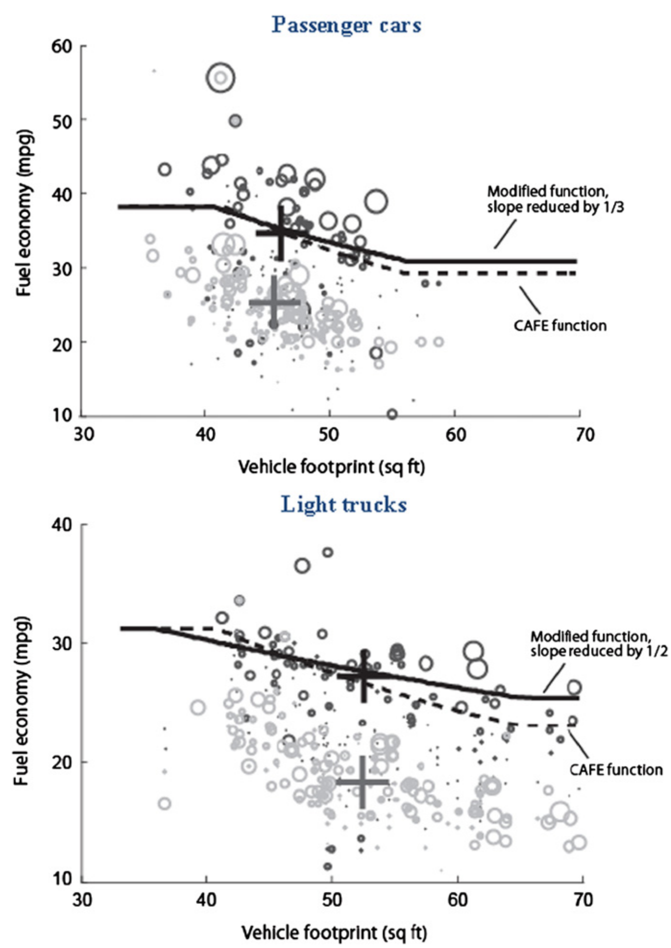

Fig. 4. Simulation results for midpoint consumer preferences with modified functions determining fuel-economy targets dependent on vehicle footprint. Sales-weighted harmonic mean vehicle attributes are represented as a cross (+). Initial data are in light gray, with MY-2014 CAFE counterfactual simulation results in dark gray. Circle size is proportional to vehicle sales.

5. Discussion

This analysis shows that the current footprint-based CAFE standards create an incentive to increase vehicle size that undermines gains in fuel economy over a large range of assumptions about consumer preferences. The hypothesis that the footprint-based CAFE standards do not create an incentive to increase vehicle size can be rejected except under somewhat extreme simultaneous assumptions regarding consumer preferences for vehicle size and acceleration performance. Assuming vehicles are driven 12,000 miles per year for 10 years and annual U.S. new vehicle sales are 13 million, results indicate that the reduction in required fuel economy caused by the incentive to increase vehicle size leads to an additional 24–76 million short tons (22–69 Mtonnes) of annual CO_2 emissions—comparable to adding 3–10 coal-fired power plants (each 1000 MW) to the electricity grid each year (Fay and Golomb, 2002).[3]

The results also suggest that the incentive to increase vehicle size is greater for light trucks than for passenger cars, which would increase the divergence of the sizes of vehicles in these classes. This divergence could negatively affect traffic safety because one can expect a divergence in the weight of vehicles in these classes corresponding to their divergence of size. Although the literature on traffic safety has not produced a consensus on the relationship between vehicle size and safety, researchers generally agree that if the spread of vehicle weight on the road increases, fatality risk in a two-vehicle crash increases (Anderson and Auffhammer, 2011; Greene and Keller, 2002; Kahane, 1997).

While the footprint-based CAFE standards can theoretically be modified to eliminate incentives to change vehicle size, this study illustrates that this process would be difficult in practice. As results illustrate, if the slope of the functions determining fuel economy targets dependent on vehicle footprint is flattened, the incentive to increase vehicle size is reduced. Results also suggest that, unless consumer preferences for vehicle size are at the lower bound and preferences for acceleration performance are at the upper bound of the ranges considered, the slope of both passenger car and light truck functions should be flattened and the slope of the function for light trucks should be flattened to a greater extent to avoid a divergence between the sizes of light trucks and passenger cars.

This analysis shows that designing the footprint-based CAFE standards such that no incentive exists to change vehicle size is complicated by the fact that this incentive depends on a number of relationships that vary among individual vehicle models. The incentive to increase vehicle size depends on engineering tradeoffs between vehicle size and other vehicle attributes, consumer preferences for all of these attributes, production costs, and competition between automotive firms. Results illustrate that the incentive to change vehicle size resulting from these factors varies substantially across individual vehicle models. Consequently, designing footprint-based fuel-economy standards in practice such that manufacturers have no incentive to adjust the size of their vehicles appears elusive at best and impossible at worst.

6. Conclusions and recommendations

This study presents an oligopolistic equilibrium model to study whether footprint-based fuel-economy standards create an incentive to increase vehicle size. Simulation results reject the hypothesis that footprint-based standards do not create an incentive to increase vehicle size over a large range of assumptions regarding consumer preference. Except for the scenarios in which consumer preference for vehicle size is at the lower bound and preference for acceleration performance is at the upper bound of ranges considered, an incentive to increase vehicle size exists and can undermine gains in fuel economy. The required fuel-economy standards from these simulation results are 1.4–4.1 mpg (0.6–1.7 km/L) lower than if vehicle size and production mix is assumed unaffected by the policy. Results also suggest that the incentive to increase vehicle size is larger for light trucks than passenger cars, which could lead to higher traffic safety risks due to the increased divergence of vehicle size between these two classes. Furthermore, this analysis illustrates that incentives to change vehicle size vary considerably between individual vehicles, suggesting that modifying the CAFE standards as they are currently structured so that manufacturers do not have incentives to change the sizes of their vehicles is extremely difficult.

In the near-term, the analysis suggests that the following three measures could help to reduce the incentive to increase vehicle size. First, the slope of the function determining fuel economy targets based on vehicle footprint should be flattened for both passenger cars and light trucks, and even further for light trucks to avoid a divergence in size between these vehicle classes. Second, potential incentives for automakers to change vehicle size in response to the CAFE standards should be carefully analyzed in all future rulemakings to inform the specific policy design. Finally, considering the sensitivity of the incentive to increase vehicle size on consumer preferences, which are likely to change over time, future rulemaking should either allow for modifications to the standards if it becomes clear that fuel-economy goals will not be met or endeavor to design the standards such that the effects of changes in consumer preferences are minimized.

In the longer term, alternative policy options should be considered to address fuel-economy goals and concerns regarding traffic safety. The ideal solution would be a policy that could assess the impact of a vehicle on total traffic safety (including the vehicle's passengers, passengers of other vehicles, and pedestrians) as well as assess the impact of the vehicle on total fuel consumption and would optimize these two objectives for the social good, giving automakers guidance on how to balance the objectives where they compete and rewarding them for developing solutions that improve both safety and fuel economy. Considering the practical difficulties of designing and implementing safety and fuel-economy regulations, however, this ideal is clearly a long way off if not impossible. All the same, policymakers and researchers should consider how to make steps toward this ideal.

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Appendix A

This appendix describes the regression analysis of the relationship between vehicle footprint and curbweight.

[3] This calculation is based on the EPA's estimates of 19.4 lb CO_2 per gallon gasoline and 22.2 lb CO_2 per gallon diesel (EPA, 2005), with gasoline vehicles making up 99% of new vehicle sales and diesel vehicles making up the remaining 1%.

Table A1
Estimates of the curbweight model in Eq. (A1).

Variable	I	II
logftp	1.3099243***	0.52676129***
height		0.00792866***
engsize		0.0613073***
_cons	3.1699523***	5.4764391***
N	472	472
r^2	0.68780556	0.80888083

*$p < 0.01$; ** $p < 0.001$; *** $p < 0.0001$.

The model of vehicle curbweight as a function of vehicle footprint is assumed to take the following form:

$$\log(wt) = \beta \log(ftp) + \gamma X + \varepsilon \tag{A1}$$

where wt is the curbweight of the vehicle, ftp is the footprint, $\mathbf{X}$ is a vector of covariates, and ε is the error term. The coefficient β is the percentage increase in curbweight resulting from a 1% increase in footprint (see for example Wooldridge 2002).

Two specifications of this model are used. The first uses no covariates; footprint is the only explanatory variable for curbweight. The second specification includes additional vehicle attributes as covariates to control for correlations in the data between footprint and other vehicle attributes that affect curbweight. Engine size (engsize) and vehicle height are included as covariates in this second specification.

Vehicle data from model-year 2006 was used to perform these regressions (Chrome Systems, Inc., 2008). Results of the three specifications are presented in Table A1. These results indicate that, when no additional vehicle characteristics are used as covariates, curbweight is estimated to increase by 1.3% for every 1% increase in footprint. When both engine size and height are controlled for in the regression, curbweight is estimated to increase by 0.53% for every 1% increase in footprint.

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