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Compliance by Design: Influence of Acceleration Trade-offs on CO_2 Emissions and Costs of Fuel Economy and Greenhouse Gas Regulations

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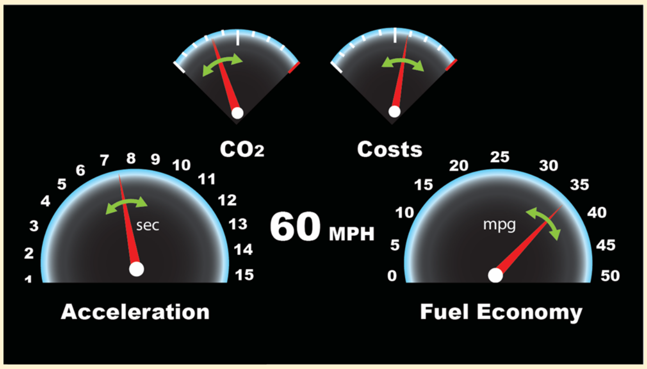
Supporting Information

ABSTRACT: The ability of automakers to improve the fuel economy of vehicles using engineering design modifications that compromise other performance attributes, such as acceleration, is not currently considered when setting fuel economy and greenhouse-gas emission standards for passenger cars and light trucks. We examine the role of these design trade-offs by simulating automaker responses to recently reformed vehicle standards with and without the ability to adjust acceleration performance. Results indicate that acceleration trade-offs can be important in two respects: (1) they can reduce the compliance costs of the standards, and (2) they can significantly reduce emissions associated with a particular level of the standards by mitigating incentives to shift sales toward larger vehicles and light trucks relative to passenger cars. We contrast simulation-based results with observed changes in vehicle attributes under the reformed standards. We find evidence that is consistent with firms using acceleration trade-offs to achieve compliance. Taken together, our analysis suggests that acceleration trade-offs play a role in automaker compliance strategies with potentially large implications for both compliance costs and emissions.



INTRODUCTION

The U.S. Corporate Average Fuel Economy (CAFE) and Greenhouse Gas (GHG) standards, issued by the National Highway and Traffic Safety Administration (NHTSA) and Environmental Protection Agency (EPA) are the principal means of reducing GHG emissions of light-duty vehicles in the United States. A significant reform of these standards occurred after the passage of the Energy Independence and Security Act (EISA) in 2007. The reformed standards do not set a fixed level of fuel economy or GHG emissions that must be met. Instead, the standards for each automaker are based on the sizes of the vehicles they produce (specifically, the vehicle's *footprint*, defined as the wheelbase multiplied by the track width) and various credits they can receive (e.g., alternative-fuel vehicle credits). The first phase of these reformed standards were enforced between 2011 and 2016. The agencies have since issued standards for 2017−2021 and are evaluating the costs and benefits of the policy to inform the final standards through 2025.

NHTSA is required to set the standards at the "maximum feasible" level, considering "technological feasibility, economic practicability, the effect of other motor vehicle standards of the government on fuel economy, and the need of the United States to conserve energy."[1] The agencies have met this requirement by determining the costs and benefits of adopting various technologies that reduce fuel consumption and GHG emissions while maintaining or improving the performance of other vehicle attributes, most notably acceleration time.[2] This cost-benefit analysis informs the standard-setting along with other considerations, such as harmonization with state GHG regulations.[3]

One advantage of the agencies' analytical approach is that it guarantees the standards can be met using available technologies, assuming vehicle demand does not change.[2] Still, nothing restricts automakers to respond to the standards the way the agencies' model predicts. Automakers have multiple compliance options available to them, and presumably choose the combination of strategies that minimize their compliance costs. Policy analyses that do not account for the full suite of compliance options may significantly overestimate compliance costs and produce misleading estimates of emission reductions.

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In addition to implementing various technology features, other possible responses to the policy include (1) trading off vehicle performance attributes (such as acceleration performance) to improve fuel economy,[4−6] (2) taking advantage of various credit provisions,[7,8] (3) adjusting prices to shift sales to vehicles that exceed their fuel economy target,[9−11] (4) increasing vehicle footprint (thereby decreasing the stringency of their fuel economy and GHG targets),[12] and (5) violating the standards and paying fines to NHTSA and civil penalties to EPA.[13−15] Previous studies have examined the influence of the latter four of these alternative strategies on fuel consumption and/or costs.[7,9−12] Whether firms have incentives to trade off acceleration performance and fuel economy in response to the reformed policy, however, has not been examined in depth.

In this paper, we investigate the role that engineering design trade-offs between acceleration performance and fuel economy can play in automakers' response to the reformed standards. To do this, we nest a flexible approximation (also called a surrogate model) of engineering design trade-offs generated from physics-based vehicle performance simulations within an economic equilibrium model of the automotive market. We then simulate the engineering design and pricing decisions of profit-maximizing firms responding to the 2014 standards with and without the ability to trade off acceleration performance.

Our analysis focuses on the compliance options that automakers can use over the "medium run", namely fuel-efficiency technologies and design trade-offs that can be implemented in the first few (i.e., 1−6) years after the regulations are announced. In order to be consistent with the agencies' approach, we do not account for design changes to vehicle footprint and compliance options that take longer production planning lead times, such as converting a significant percentage of their fleet to electric vehicles.[13] However, we also find that our conclusions are robust to relaxing the technology assumptions.

Unlike the agencies' analysis, which assumes vehicle-specific demand is fixed, our model allows demand to respond to policy-induced changes in vehicle prices and attributes. This demand response is important to consider when assessing the significance of acceleration trade-offs. In contrast with fuel-efficiency technologies that increase vehicle production costs, the primary costs to automakers of compromising acceleration performance are lost profits due to reduced demand and/or lower markups necessary to achieve a particular level of demand.

Acceleration trade-offs can lower the compliance costs associated with the regulation in three related ways. First, an automaker may find it relatively more profitable to compromise the acceleration performance of its vehicles (to improve fuel economy) rather than incorporating additional costly fuel-saving technologies or changing prices to shift demand to more fuel-efficient vehicles. Second, automakers may prefer to use acceleration trade-offs in combination with technology features in some or all of their vehicles so that fuel economy improves as well as acceleration performance. Third, if the regulation induces worse acceleration performance in some vehicles, competition for consumers who value acceleration will be reduced. This may cause some automakers to *improve* the acceleration performance of certain vehicles (in order to attract these consumers) at the expense of fuel economy, while simultaneously improving the fuel economy of other vehicles enough to comply with the standards.

This paper contributes to a growing body of literature that examines the economic and environmental impacts of fuel economy and GHG standards. Recent research finds that manufacturers can use a variety of loopholes and other compliance mechanisms that relax the stringency of the standards, leading to higher emissions.[7,8,12,15,16] If acceleration trade-offs offer a relatively cost-effective means of complying with the standards, automakers' incentives to exploit these mechanisms that relax the stringency of the standards will be reduced.

Our work also begins to bridge a gap between the engineering design and economics literatures examining firms' optimal product design and pricing decisions. The approach we take is designed to leverage the relative strengths of methods in each field. Recent work in the economics literature uses bundles of attributes observed in the marketplace to econometrically estimate engineering trade-offs between energy efficiency and other product attributes.[5,11,17,18] The most closely related example is Klier and Linn (2012), who examine the influence of trade-offs between fuel economy and engine power in the context of the prereform CAFE standards. One limitation of this approach is that many combinations of product attributes are not observed in the marketplace, but are technologically feasible and potentially optimal under future policy scenarios. A second concern is that correlations between attributes of interest (e.g., energy efficiency) and attributes that are difficult to quantify or otherwise unobservable in historical data (e.g., vehicle shape) can make it difficult to identify attribute trade-offs econometrically. The physics-based engineering simulations we use to characterize design trade-offs can identify technologically possible combinations of attributes that have yet to manifest in existing product designs. This approach also allows us to identify trade-offs independently of unobserved product attributes.

The engineering design literature, on the other hand, develops detailed models of the trade-offs among product attributes based on physics.[19−21] In this literature, it is common to determine a particular firm's choices of engineering design variables and prices that maximize the firm's profits.[22−24] With a few notable exceptions,[25−29] however, this body of research generally ignores the strategic nature of competing firms' price and design decisions. The studies that do account for competitor design and pricing decisions are focused on relatively simple examples with ten or fewer products in the market and identical design trade-offs and costs for all firms. We extend this literature by nesting an engineering-design model of heterogeneous firms producing many product variants (a total of 471 distinct vehicle models and engine options) in an economic equilibrium model that captures the strategic competition between automakers. This extension is significant because the strategic interactions between competing firms and the industry structure affects firms' profit-optimal designs and prices,[25,29] and therefore resulting emissions and costs.

■ MATERIALS AND METHODS

To capture the trade-offs between acceleration performance and fuel economy, we implement thousands of vehicle performance simulations over a range of feasible vehicle design configurations using an engineering simulation software package (AVL Cruise) that is used by the automotive industry to support the powertrain development process. To incorporate these simulated data in our model in a tractable way, we estimate a flexible approximation of the relationships among vehicle performance attributes and production costs. These estimated relationships are then nested within an oligopolistic equilibrium model of the automotive market.

On the supply side, we include the 18 automakers that comprise 97% of the U.S. market. We assume each firm chooses prices and design variables for each of their vehicle models and engine options (e.g., the Toyota Camry with a 2.5 L engine and with a 3.5 L engine) to maximize profits. More specifically, we allow automakers to adjust fuel consumption (measured as gallons of fuel consumed per 100 miles) and acceleration (measured as the time in seconds to accelerate from 0 to 60 mph) by modifying powertrain tuning variables and technology features that can be changed in the medium run during vehicle redesign. We hold fixed the vehicle design parameters that are determined in earlier stages of the vehicle development process (see Supporting Information (SI) S1.1 for details). Longer-run design parameters include vehicle segment (e.g., midsize sedan), the powertrain architecture (e.g., conventional gasoline, hybrid, or diesel), and key internal and external dimensions.[30−32]

On the demand side, a random-coefficient logit discrete choice model is estimated using household-level data on vehicle purchase decisions. Taken together, the supply and demand-side models can be used to simulate how automakers' profit-maximizing choices of vehicle designs and prices change in response to the 2014 standards, and the resulting impact on emissions and costs in equilibrium. To evaluate how acceleration trade-offs affect these outcomes, we generate two sets of simulations: (1) a model where automakers can adjust acceleration performance and fuel consumption, and (2) a more restricted model where acceleration performance is held fixed for all vehicles.

We choose 2006 as the reference year for consumer preferences and "baseline" vehicle designs to which automakers can add technology options and adjust powertrain tuning variables. This was the year immediately preceding the passage of EISA. After this year, automakers presumably began to plan their compliance strategies, and in some cases, implement design changes to earn early compliance credits.

Engineering Design Trade-offs. We make a conceptual distinction in our modeling framework between two types of engineering design modifications that automakers can use to change the fuel economy of their vehicles in the medium-run. *Powertrain tuning variables* (e.g., the final drive ratio) can be adjusted to favor fuel economy over acceleration performance or vice versa and have negligible influence on production costs or lower these costs. *Technology features* can be incorporated into a vehicle at an extra cost to improve fuel economy. Examples of technology features include high-efficiency alternators, low resistance tires, and low-friction materials in the engine. Many (although not all) of these technology features improve acceleration performance in addition to fuel economy.

As we discuss below, our model of the vehicle development process is not comprehensive. Because of simulation and data constraints, we do not account for all powertrain tuning variables and technology features automakers have at their disposal in the medium-run to increase fuel economy (e.g., changing the number of transmission gear ratios). If excluded powertrain tuning variables or technology features are less cost-effective to change than those explicitly accounted for, omitting them will be inconsequential. If any of the omitted powertrain tuning variables are more cost-effective, our results represent lower bounds of the impact that design trade-offs can have on emissions and costs. However, if omitted technology features are more cost-effective than those we include, the influence of acceleration trade-offs would be overestimated. To assess the robustness of our findings to the set of technology features considered, we conduct sensitivity tests of our results to extending the technology improvements possible and lowering technology costs.

Our modeling of vehicle design trade-offs begins with the construction of "bundles" of design variables specific to each vehicle segment, s, indexed $b = 1 \cdots B$. Each bundle is comprised of a set of powertrain tuning variables, $\boldsymbol{x}_s$, and technology features, t_s, that firms are able to adjust in our equilibrium model, as well as fixed design parameters, $\tilde{x}_s$, which firms cannot change. In the model, there are two powertrain tuning variables that can be manipulated to trade off acceleration performance for improved fuel economy: engine displacement size and the final drive gear ratio in the transmission. Fixed design parameters consist of vehicle segment, baseline curbweight (i.e., the weight of the vehicle without any passengers or cargo and without substituting existing materials for lightweight materials), gradeability (i.e., the steepest hill a vehicle can climb maintaining a particular speed), and towing requirements. Our classification of vehicle parameters as adjustable or fixed is based on the structure of the vehicle development process and manipulability of these parameters over the medium run as described in detail in SI S1.1. Technology features are taken from NHTSA's analysis of available fuel-saving technologies based on independent studies and information from automotive manufacturers, researchers, and consultants (SI Table S2).[33]

We use the vehicle performance simulation package AVL Cruise to calculate the fuel consumption per 100 miles (fuelcons) and 0−60 mph acceleration time (acc) of a particular vehicle design conditional on a specified bundle of design parameters, b. We generate almost 30 000 sets of simulation results, each representing the fuel consumption and acceleration performance corresponding to the bundle of design parameter inputs, which are varied at small increments. Additional details of the vehicle simulations are discussed in SI S1.3.

The relationship between adjustable powertrain tuning variables and production costs is taken from Michalek et al., who estimate the relationship using data from automotive manufacturers and wholesale and rebuilt engine suppliers.[27] Production costs associated with the addition of specific technology features are taken from NHTSA's analysis (SI Table S2), which were used in cost-benefit analyses of the regulations.[33] NHTSA collected these cost data from vehicle tear-down studies, confidential manufacturer information, and independent studies. Cost reductions due to learning in the time between the announcement of the reformed regulations and their implementation are incorporated into the agencies' estimates (see SI S1.6−1.8 for a detailed description of the data). Similar to the agencies' approach, we assume that all changes to vehicle designs occur during regularly scheduled product redesign cycles and so do not incur additional costs that would be associated with modifying the medium-run vehicle design variables in later stages of the development process.[34]

Because changes to the final drive ratio negligibly influence production costs, for any chosen values of acceleration performance and technology features, there is only one choice of $\boldsymbol{x}_s$ that minimizes the production costs, c, associated with a given level of fuel consumption (see SI S1.4 for a detailed explanation). The engineering design trade-offs we model can thus be summarized by a system of two equations representing the efficiency frontiers (called Pareto frontiers in the engineering design literature) of fuel consumption and production costs for a particular vehicle design as a function of its acceleration performance and technology features, conditional on fixed design parameters (derivations are provided in SI S1.4 and S1.6): $\mathrm{fuelcons}_{\mathrm{sb}} = h_{1s}(\mathrm{acc}_{\mathrm{sb}}, t_s; \tilde{x}_s)$, $c_{\mathrm{sb}} = h_{2s}(\mathrm{acc}_{\mathrm{sb}}, t_s; \tilde{x}_s)$.

While we could in principle specify the structure of these two functions and estimate the parameters separately for all possible combinations of technology features, in practice it is computationally infeasible to explicitly incorporate this large number of discrete technology combinations in our equilibrium simulations. For the purpose of tractability, we approximate the set of cost-effective technology feature combinations with a single continuous variable, tech. The tech variable takes on a value between zero (the baseline case) and the maximum number of cost-effective combinations of technology features for each vehicle segment, with each value mapping to a specific combination of technology features. These technology combinations are ordered by decreasing fuel consumption for the same acceleration time, which is also increasing in cost. Therefore, a higher value of tech corresponds to a lower fuel-consumption and higher cost vehicle conditional on 0–60 mph acceleration time.

Several parametric specifications of the fuel consumption and cost functions were estimated using the vehicle simulation and production cost data. The following specifications performed the best under the Akaike Information Criterion:

$$\begin{aligned}\mathrm{fuelcons}_{\mathrm{sb}} = \kappa_{1\mathrm{s}} + \kappa_{2\mathrm{s}}\mathrm{e}^{-\mathrm{acc}_{\mathrm{sb}}} + \kappa_{3\mathrm{s}} wt_{\mathrm{sb}} + \kappa_{4\mathrm{s}} wt_{\mathrm{sb}}\cdot\mathrm{acc}_{\mathrm{sb}} \\ + \kappa_{5\mathrm{s}}\mathrm{tech}_{\mathrm{sb}} + \kappa_{6\mathrm{s}}\mathrm{tech}_{\mathrm{sb}}\cdot\mathrm{acc}_{\mathrm{sb}} + \epsilon_{\mathrm{sb}}\end{aligned} \tag{1}$$

$$\begin{aligned}c_{\mathrm{sb}} = \sigma_{1\mathrm{s}} + \sigma_{2\mathrm{s}}\mathrm{e}^{-\mathrm{acc}_{\mathrm{sb}}} + \sigma_{3\mathrm{s}} wt_{\mathrm{b}} + \sigma_{4\mathrm{s}} wt_{\mathrm{b}}\cdot\mathrm{acc}_{\mathrm{sb}} + \sigma_{5\mathrm{s}}\mathrm{tech}_{\mathrm{s}} \\ + \epsilon_{\mathrm{sb}}\end{aligned} \tag{2}$$

where fuelcons, c, acc, and wt, are the fuel consumption, marginal production costs, 0–60 mph acceleration time, and the curbweight of a vehicle in segment s with bundle of design variables b. We show in SI S1.9 that these particular specifications preserve important relationships between fuel consumption, acceleration performance, technology features, and costs from the underlying vehicle performance simulations and cost data.

Estimated values of the parameters in eqs 1 and 2 are reported in SI Tables S3 and S4. The models fit the data in each segment reasonably well ($R^2 = 0.81–91$) with the exception of the two-seater segment ($R^2 = 0.67$ for fuel consumption and 0.75 for costs). However, this segment comprises less than 1% of vehicle sales so the poorer fit should not significantly affect the policy simulation results.

Demand Model. Following Train and Winston (2007), we model consumer vehicle choices using a random-coefficient logit model estimated using data on consumer-level choices and vehicle attributes. The utility consumer n derives from vehicle model and engine option i can be decomposed into four components:

$$u_{ni} = \delta_i + \sum_{\mathbf{kr}} a_{ik} z_{nr} \beta_{kr} + \sum_{\mathbf{k}} a_{ik} \nu_{nk} \mu_k + \epsilon_{ni} \tag{3}$$

The first component, δ_i, captures the average utility across consumers for a specific vehicle model and engine option. $\delta_i = \sum_k a_{ik}\overline{\beta_k} + \xi_i$ where each a_{ik} is an observable vehicle attribute, such as price and fuel economy, $\overline{\beta}_k$ is the coefficient for the attribute, and ξ_i captures the utility of attributes valued by the consumer but not observed in the data (e.g., interior materials). The second component represents the portion of utility for vehicle attributes that varies systematically with observed consumer characteristics, $\boldsymbol{z}_n$. The third component captures the effects of interactions between vehicle attributes and consumer characteristics we cannot observe. This allows for random variation in consumer preferences for specific vehicle attributes, $\boldsymbol{\mu}$, which are assumed to be normally distributed.

The fourth term, ϵ_{nj}, in eq 3 captures idiosyncratic individual preferences. We invoke the standard assumption that these errors have an i.i.d. Type I extreme value distribution. This assumption yields the following functional form for the vehicle-choice-share probabilities, P_{ni}, conditional on $\boldsymbol{z}_n$, $\boldsymbol{\nu}_n$, and the parameters to be estimated, $\boldsymbol{\theta}$.

$$\begin{aligned}P_{\mathrm{ni}} = \Pr(y_n = i|z_n, \nu_n, \boldsymbol{\theta}) = \frac{\exp(\delta_i + \sum_{\mathbf{kr}} a_{ik} z_{nr} \beta_{kr} + \sum_k a_{ik} \nu_{nk} \mu_k)}{1 + \sum_j \exp(\delta_j + \sum_{kr} a_{jk} z_{nr} \beta_{kr} + \sum_k a_{jk} \nu_{nk} \mu_k)} \\ \equiv \frac{\exp(u_{ni})}{1 + \sum_j \exp(u_{nj})}\end{aligned} \tag{4}$$

The predicted sales of vehicle i is $M\sum_n P_{\mathrm{in}} \equiv q_i$ where M is the market size. This utility formulation is extended to include consumers' ranked choices when available (see SI S3.2).

Because unobserved vehicle attributes that consumers value, such as interior materials, acoustic performance, and electronic accessories, are likely to be correlated with the vehicle attributes of primary interest (namely, price, fuel economy, and acceleration performance), estimating eq 4 for $\overline{\beta}_k$ directly will likely yield biased estimates. This well-documented endogeneity problem is typically addressed using an instrumental variables (IVs) strategy.[35−38] It has become standard to use functions of nonprice attributes, $\boldsymbol{w}$, including horsepower and fuel economy, as IVs for endogenous attributes.[35−39] This strategy is predicated on an exclusion restriction that requires the IVs to be exogenous such that $\mathbb{E}[\xi_i|\mathbf{w}] = 0$. Our study is motivated by the observation that automakers can modify vehicle attributes such as fuel economy and horsepower in the medium-run. Thus, in contrast to earlier studies, we use only those vehicle attributes that are determined by longer run product-planning schedules as IVs for price, fuel economy, and acceleration performance. Specifically, we use the moments of vehicle dimensions of same-manufacturer vehicles and different-manufacturer vehicles, powertrain architecture (e.g., hybrid, diesel, conventional gasoline), and drive type (e.g., all wheel drive). This identification strategy is discussed in more detail in SI S3.3.

Two sources of data are used to estimate the demand model: a detailed household-level survey conducted by Maritz Research in 2006, and vehicle characteristic data available from Chrome Systems Inc. SI S3.1 describes these data and reports the estimated parameters in SI Tables S8 and S11. We perform random initial value tests and verify that the algorithm converges to the same solution.

Automotive Oligopoly Model. To model firms' product pricing and design decisions, we nest the engineering design and demand models summarized by eqs 1–4 within a differentiated product oligopoly model. We assume that firms choose the prices, acceleration performance, and levels of technology features of all the vehicle models and engine options they produce to maximize profits, π, according to the following formulation.

$$\max_{p_j, \mathrm{acc}_j, \mathrm{tech}_j \forall j} \pi = \sum_j q_j(p_j - c_j)$$

$$\text{subject to } \mathrm{CAFE}_l^{\mathrm{TARGET}} - \mathrm{CAFE}_l - \mathrm{credit}_l \leq 0 \ \forall\, l$$

$$\text{where } q_j = g(p_j, \mathrm{fuelcons}_j, \mathrm{acc}_j; \tilde{x}_j)$$

$$\mathrm{fuelcons}_j = \mathrm{h}_1(\mathrm{acc}_j, \mathrm{tech}_j; \tilde{x}_j)$$

$$c_j = \mathrm{h}_2(\mathrm{acc}_j, \mathrm{tech}_j; \tilde{x}_j) \tag{5}$$

The variables q_j, p_j, and c_j are, respectively, the quantity demanded, price, and marginal cost associated with vehicle model and engine option j. The standards are represented as a constraint for each vehicle class l (i.e., passenger cars and light trucks). We define CAFE_l to be the harmonic sales-weighted average fuel economy of all vehicles in class l that the firm produces, which must equal or exceed the firm's CAFE target for that vehicle class, $\mathrm{CAFE}_l^{\mathrm{TARGET}}$, within allowable fuel-economy credit provisions defined by the regulations, credit_l. Excluding differences between noncompliance penalties and the credits automakers can earn under the CAFE and GHG standards (i.e., AFV and off-cycle credits), the standards are equivalent. Therefore, in the case where firms meet the standards without the use of these credits, both standards can be represented by the single constraint for each vehicle class in eq 5. We repeat the simulations under alternative assumptions to explore scenarios under which automakers can earn additional credits under the CAFE and GHG standards (see SI S4.3).

For the main specification presented in this paper, we allow all firms to trade credits between their passenger car and light truck fleets but we constrain firms to comply with the 2014 standards without further credit provisions. We use our oligopoly model to simulate the effects of replacing the unreformed 2006 standards with the 2014 reformed standards with and without the consideration of acceleration trade-offs. We use 2006, which just predates the policy reform, as a baseline against which we determine emission reductions, changes in vehicle attributes, and producer and consumer costs. To avoid confounding the effects of the policy reform with our modeling assumptions (including any model misspecification and the omission of some credit provisions) as well as the exogenous reduction of technology costs over time, we use *simulated* partial equilibrium outcomes under the 2006 standards as our baseline rather than observed data. A comparison of the simulated baseline outcomes with observed attributes is provided in SI S4.1. In order to build confidence in our simulations, we perform out-of-sample predictions of sales-weighted average fuel economy and acceleration performance in the years between 2006 and 2014 and compare them to observed values in these years. We find that the simulations predict observe values within 3% for each year (see SI S4.5).

■ SIMULATION RESULTS

The model is used to simulate a series of vehicle-specific equilibrium outcomes: fuel economy, acceleration performance, technology features, prices, production costs, and vehicle sales. These simulated outcomes are used to calculate total use-phase GHG emission reductions over the lifetime of the vehicles and producer and consumer costs resulting from replacing the 2006 standards with the 2014 standards. GHG emissions are calculated assuming passenger cars and light trucks are respectively driven 195 000 and 226 000 miles over their lifetime in the baseline with a rebound effect of 10.3%.[40,41] Producer costs are measured in terms of profit losses relative to the baseline. Consumer costs are measured in terms of consumer surplus losses calculated by equivalent variation, or the amount that a consumer would need to be paid to realize the same amount of utility. We determine the compliance costs of the policy in terms of the sum of profit losses and consumer surplus losses (hereafter, social surplus losses) per ton of emissions reduced. We stop short of a comprehensive measure of the societal benefits (e.g., improved air quality) associated with reduced fuel consumption and GHG emissions in these calculations.

In addition to assessing the extent that acceleration trade-offs influence GHG emissions and social surplus, we investigate two "offsetting" effects that play a role in determining the net effect of the reformed standards on aggregate emissions. The first relates to the differences in stringency between the passenger-car and light-truck standards. If the market share of light trucks rises relative to that of passenger cars, GHG emissions will be higher. The second relates to the fact that the standards are size-based. Firms can reduce the stringency of the standards by shifting sales toward larger passenger cars and light trucks.

Table 1 summarizes simulation results for two scenarios: (1) modeling trade-offs between fuel economy and acceleration performance, and (2) excluding these trade-offs. In the simulation that include design trade-offs, we see significant compromises in acceleration performance. Average 0−60 mph acceleration time increases 0.7 s or approximately 8% (an increase in acceleration time means acceleration performance is worse). Notably, the large majority of this change comes from the design response versus changes in sales composition. In the simulations that shut off the design trade-offs, we see a relatively small increase in acceleration time, which is driven entirely by changes in sales composition.

Table 1. Simulation Results of the Impact of Replacing the 2006 Standards with the 2014 Standards in Simulations Excluding and Including Acceleration (acc) Trade-Offs; Both Scenarios Account for Price Changes and Adoption of Fuel-Saving Technology Features

	no acc trade-offs	with acc trade-offs
Emissions and Social Surplus Results		
change in CO_2 emissions (million metric tons)	−18.8	−76.5
change in consumer surplus (billions 2014 USD)	−\$12.8	−\$7.4
change in producer profits (billions 2014 USD)	−\$0.2	−\$0.1
Aggregate Vehicle Attribute Results		
change in sales-weighted average fuel economy (mpg)	+0.7	+2.6
change in sales-weighted average acceleration (s)	+0.1	+0.7
change in sales-weighted average footprint (sq ft)	+1.2	+0.1
change in share of light trucks	+3.5%	+2.7%

Results indicate that, when acceleration trade-offs are considered, GHG emission reductions increase from 19 to 77 million metric tons. There are two key reasons for this that are related to changes in the composition of new cars sold. First, the market share of light trucks increases more when acceleration trade-offs are shut off. Second, the sales-weighted average vehicle footprint increases by 1.0 sq. ft (0.09 m^2) when acceleration trade-offs are excluded, whereas it remains approximately the same when they are included. Recall that we do not allow firms to change the footprint of their vehicles in our simulations, so this increase in size is due to price changes that shift demand to larger passenger cars and light trucks (see Whitefoot and Skerlos[12] for an analysis of size increases when footprint-design changes are possible).

Social surplus is also significantly impacted by acceleration trade-offs. Policy-induced consumer surplus losses decrease from $12.8 billion or approximately $790 per consumer to $7.4 billion or approximately $460 per consumer when the trade-offs are included. Total profit losses are reduced from $200 million to $100 million, which should be considered upper bounds because we do not account for all compliance flexibilities in the regulations (e.g., banking and borrowing of credits). Total social surplus losses when attribute trade-offs are excluded are comparable to results in Klier and Linn's (2012) study of the prereform regulations after adjusting for the stringency of the reformed standards (see S4.4 for details). The change in social surplus when attribute trade-offs are included, however, is smaller than that reported in Klier and Linn. This is most likely due to a combination of two factors. First, our estimates of attribute trade-offs using physics-based vehicle simulations imply that fuel consumption can be reduced with smaller adjustments in acceleration performance than econometric estimates that may conflate trade-offs with unobserved vehicle attributes correlated with fuel economy and acceleration (see S2). Second, the reformed policy differs from past regulations in several important ways that reduce costs for compliant firms (e.g., reducing leakage by enforcing tough penalties for firms that violate the GHG standards). Similar to most prior studies, we find that the vast majority of the costs of the policy are passed on to consumers.

The simulated average impacts on vehicle attributes mask significant heterogeneity across vehicles. Figure 1 shows the policy-induced changes in sales-weighted average fuel economy and acceleration times and the spread between the 10th and 90th quantiles. As the figure illustrates, there are mostly increases, but also some notable decreases, in these attributes when acceleration trade-offs are included. Recall that automakers may reduce the fuel economy of some vehicles in favor of acceleration performance to attract consumers willing to pay for superior acceleration performance. Our simulation results show that for 25% of vehicles, firms choose to reduce fuel economy in order to improve acceleration performance. For 57% of vehicles, automakers rely on compromising acceleration performance rather than relying on fuel-saving technology features to improve fuel economy, and for 17% they use a combination of acceleration trade-offs and technology features. Less than 1% have no change in acceleration performance. We also find heterogeneity across automakers. Some firms rely on acceleration trade-offs to comply with the standards to a much greater extent than others.

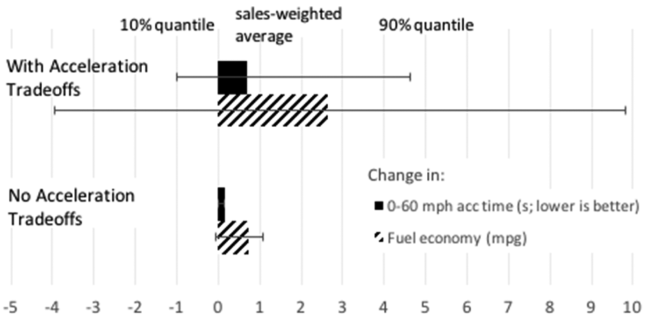

Figure 1. Simulation results of changes in vehicle attributes in response to the reformed standards when trade-offs between fuel economy and acceleration (acc) are considered and when they are excluded from the analysis. The sales-weighted averages for fuel economy are harmonic averages following the policy, whereas arithmetic averages are used for acceleration.

We also conduct sensitivity tests that examine the effect of varying the estimates of technology feature costs and consumer willingness-to-pay for fuel economy. Results are summarized in Table 2. When consumers are willing to pay more for improvements in fuel economy, the influence of acceleration trade-offs on emissions and compliance costs is lower than in the main simulation specification. The change in GHG emission reductions due to acceleration trade-offs drops from 58 million metric tons to 32 and reductions in compliance costs drop from 5.5 billion to 2.2. This occurs because the standards are effectively less stringent so that the benefits of using acceleration trade-offs as an additional compliance strategy is smaller (although still substantial). Intuitively, acceleration trade-offs also have a somewhat smaller impact on emissions and compliance costs when fuel-saving technology costs are lower and when the upper bound of the tech variable is relaxed.

Table 2. Influence of Acceleration Trade-Offs on Simulation Results of the 2014 Policy Outcomes under Alternate Specifications[a]

	change in CO_2 emissions (million metric tons)	change in compliance costs (billion 2014 USD)
main specification	−58	−5.5
Sensitivity Tests on Main Specification		
willingness to pay for fuel economy 35% higher	−32	−2.2
cost of tech features 25% lower	−48	−4.7
maximum tech 10% higher	−54	−3.7

[a]The table presents the *difference* between the estimates produced from the simulations where acceleration trade-offs are included with the estimates produced by the simulations that exclude these trade-offs.

LONGITUDINAL REGRESSION OF OBSERVED ACCELERATION

The simulation results summarized above predict how the reformed policy affects acceleration trade-offs, emissions, and compliance costs conditional on modeling assumptions and holding other confounding factors (such as fuel prices) constant. These simulations are based entirely on data that was available before the policy change in order to be consistent with the type of analysis agencies could perform when assessing the impact of future policy options.

As a check on the simulation results, we also examine acceleration trade-offs using a completely different method: a longitudinal regression analysis of the acceleration performance we observe in the new vehicle market before and after the reformed standards took effect. We use data on sales-weighted attributes collected by EPA for 1976−2014 vehicles.[42] These data are recorded at the level of firm-year for each vehicle class. Although the reformed standards did not apply until 2011, automakers could earn credits for earlier action, which they could use to comply with the standards once they took effect.[43] For this reason, we look for evidence of policy-induced design changes as early as 2007 (after EISA was passed).

Empirically estimating the causal effect of the policy reform on vehicle attributes is difficult because there are many time-varying factors that could influence vehicle design choices. Potentially confounding factors include exogenous technological change, rising gasoline prices, and evolving consumer preferences. In order to isolate the effect of the reformed standards on vehicle design choices as best we can with the available data, we include several controls for these time-varying factors in our analysis.

We use 30 years of data prior to the announcement of the reformed policy to analyze trends in acceleration performance over time. The following equation serves as the foundation for our empirical analysis:

$$\mathrm{acc}_{it} = \alpha + \delta(t) + \beta' X_{it} + \gamma_1 \mathrm{D1}_t + \gamma_2 \mathrm{D2}_t + \varepsilon_{it} \qquad (6)$$

where i indexes manufacturing firms and t indexes time (measured in years). The $\delta(t)$ function models acceleration performance as a function of time. X_{it} captures time varying determinants of acceleration performance such as gasoline prices. D1 and D2 are policy indicators that equal one one after MY2006 and MY2010, respectively, and zero before. Including these binary policy indicators allows a level shift in acceleration performance trends after the policy takes effect. We also estimate a linear spline function which allows the slope of the acceleration performance trajectory to change as firms begin to comply with the policy. In the spline specifications, binary indicators in eq 25 are replaced with $\mathrm{B1}_t = t$-2006 and $\mathrm{B2}_t = t$-2010.

Results are summarized in Table 3 (additional specifications are described in the SI). Relative to the trends and relationships observed prior to the reformed standards, we find that the rate of improvement in acceleration performance slowed after the policy reform was announced and slowed further once the policy took effect. These policy variables are jointly significant. The preferred specifications are (2) and (4), which condition on real gasoline prices. These estimated coefficients can be used to impute an effect of the policy on sales-weighted average 0−60 mph acceleration time. The table reports these imputed effects which range from 0.63−1.10 s slower. For the preferred specifications, the estimated effects of the policy on average acceleration are remarkably similar to our simulation-based estimate of 0.7 s.

Analyzing these same data at the firm-level reveals substantial heterogeneity in patterns of acceleration performance across manufacturers. For each firm and vehicle type (i.e., passenger car or light truck), we construct the counterfactual trajectory of acceleration performance by extrapolating prepolicy acceleration trends controlling for time-varying factors. Observed acceleration following the introduction of the reformed standards underperforms relative to this counterfactual for most firms. For some firms, however, we estimate improvements in acceleration performance among passenger cars (Kia) and trucks (Chrysler, Ford, and Mercedes-Benz). These firm-level estimates are summarized in SI Table S14. While the firm-level heterogeneity is qualitatively consistent with our simulation results, firm-level estimates of acceleration time vary substantially between the two approaches.

Table 3. Regression Analysis of Sales-Weighted Average Acceleration Performance over the Period 1976−2014[a]

	(1)	(2)	(3)	(4)
time trend	−0.181[b]	−0.174[b]	−0.182[b]	−0.176[b]
	(0.014)	(0.012)	(0.014)	(0.012)
D1	0.523[b]	0.161		
	(0.202)	(0.165)		
D2	0.571[b]	0.467[b]		
	(0.180)	(0.166)		
real gasoline prices		0.261[d]		0.270[d]
		(0.158)		(0.148)
B1			0.195[b]	0.070
			(0.070)	(0.049)
B2			−0.074	0.082
			(0.061)	(0.053)
Constant	15.008[b]	14.293[b]	15.024[b]	14.307[b]
	(0.363)	(0.553)	(0.362)	(0.514)
imputed impact of the policy on acceleration (s)	1.1	0.63	1.1	0.71
joint F-test	5.37[c]	4.01[c]	8.22[b]	8.57[c]
R^2	0.750	0.754	0.753	0.757
number of observations	493	493	493	493

[a] The unit of observation is a firm-year-vehicle type. [b] $p < 0.01$. [c] $p < 0.05$. [d] $p < 0.1$.

In sum, the trajectories in acceleration performance we observe are qualitatively consistent with our simulation results; following the introduction of the reformed policy, observed acceleration performance is significantly worse than our counterfactual estimate based on trends before the policy change. Our estimated impact of the reformed standards on sales-weighted average acceleration performance are very similar across our econometric and simulation results, although the firm-level results are not as congruent. These results lend further support to our hypothesis that acceleration trade-offs play an important role in automakers' compliance strategies.

■ CONCLUSION

Environmental policies can significantly influence engineering design decisions as firms reoptimize their products to meet compliance requirements at minimum cost. We evaluate the potential importance of vehicle design trade-offs between fuel economy and acceleration performance in automakers' responses to the reformed CAFE and GHG standards. Using simulations of the automotive industry, we find that automakers have an incentive to use these design trade-offs and that GHG emissions and compliance costs (measured in terms of lost producer profits and consumer surplus) are significantly lower when these trade-offs are accounted for. We also find that these simulation-based estimates are consistent with changes in vehicle attributes observed in the years following the announcement of the policy. Given the potential importance of acceleration trade-offs as a means of complying with vehicle standards, regulatory agencies should consider these performance trade-offs. Our results also imply that previous analyses of the regulations that do not include these trade-offs may significantly overestimate compliance costs and underestimate GHG emission reductions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b03743.

> Detailed information on each of the constituent data and models used in our analysis as well as descriptions of several robustness checks on our results (PDF)

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Notes

The authors declare no competing financial interest.

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