Estimating the Costs and Benefits of Fuel-Economy Standards

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Executive Summary

Fuel-economy standards for new vehicles are a primary policy instrument in many countries to reduce the carbon footprint of the transportation sector. These standards have many channels of costs and benefit, affecting sales, composition, vehicle attributes, miles traveled, and externalities in the new-car fleet, as well as the composition and size of the used fleet. We develop a tractable analytical framework to examine the welfare effects of fuel-economy standards and apply it to the recent government proposal to roll back fuel-economy standards. We find that our combined, multimarket vehicle-choice model implies that the proposal would increase the size of the vehicle fleet over time and generates smaller welfare gains than models with a less rich structure of the vehicle market, such as the one used in the analysis associated with the 2018 Notice of Proposed Rulemaking (NPRM) announcement. The disparities across the two models appear to result from the absence of feedback effects in the NPRM analysis. We stress the importance of instead using a multimarket vehicle-choice model to provide the most accurate predictions of costs and benefits. We also derive bounds that can serve as a check on the theoretical consistency of such analyses and that offer insights into the magnitudes of potential errors resulting from imperfect multimarket integration.

JEL Codes: H23, L51, Q38, Q48, Q58

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I. Introduction

Since the mid-1970s the United States has had Corporate Average Fuel Economy (CAFE) standards. Although the details have changed somewhat over time, under CAFE standards, the average fuel economy of automobile manufacturers must be at or above a certain level. The

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actual fuel-economy standard increased significantly during the late 1970s and early 1980s, but it was effectively unchanged from 1990 to the mid-2000s. Figure 1 shows the standards. As noted in the figure, a different standard is set for light-duty trucks (a category that includes SUVs, minivans, and pickups) and passenger cars.

The Obama administration adopted a new set of standards in 2011. A number of notable changes were made. First, the standards switched to being based on "footprint"—the area defined by the four points where the tires touch the ground. It is calculated as the product of the wheelbase and the average track width of the vehicle. The larger the footprint, the lower the standard (in miles per gallon, or MPG). Given this change, manufacturers face different standards depending on the sales-weighted average of the footprints of their vehicles. A second change under the Obama administration's CAFE was that both the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) administered separate but related standards. The NHTSA standard is based on fuel economy, whereas the EPA's standard is based on tailpipe CO_2 emissions. Historically, only the NHTSA administered

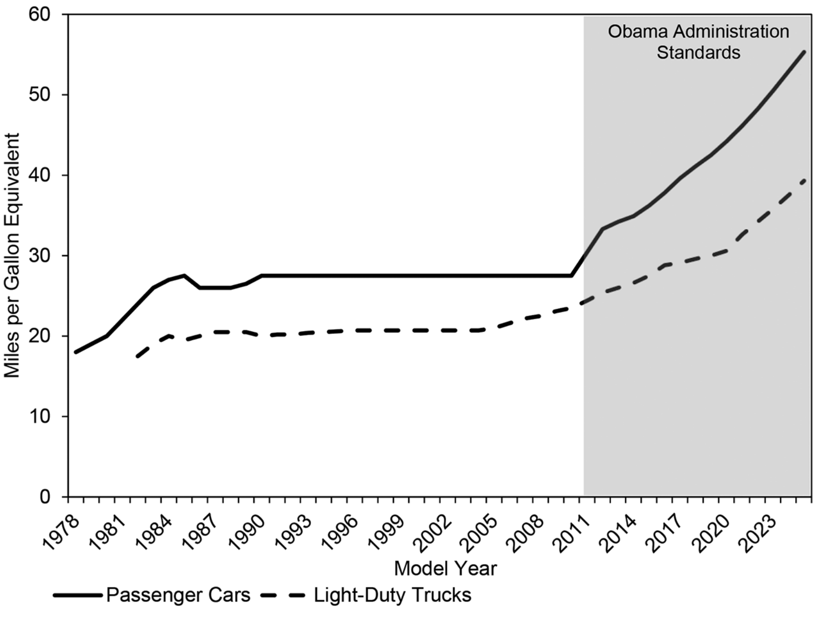

Fig. 1. US Corporate Average Fuel-Economy standards over time
Source: US DOE (n.d.).

CAFE. Third, the new standards in 2011 allow for "compliance trading" across manufacturers: automakers that exceed the standards can sell their excess compliance credits to firms that underperform, adding flexibility in compliance channels.

The economics of fuel-economy standards is fairly straightforward. Such standards are an example of performance standards, in which a regulator mandates an average emissions rate but does not require firms to employ specific technologies. Kwoka (1983) works through the underlying economics of fuel-economy standards, whereas Holland, Hughes, and Knittel (2009) present additional results related to performance standards more generally. The intuition is straightforward. Consider a manufacturer facing a fuel-economy standard such that the average fuel economy of its vehicles has to be at least 30 MPG. Now, consider a firm that sells two vehicles: one has a fuel economy of 25 MPG; the other has a fuel economy of 35 MPG. Furthermore, the fuel-economy constraint is binding in the sense that absent the regulation the firm would choose to sell a mix of vehicles with an average fuel economy below 30 MPG. When facing the 30 MPG standard, the firm has less of an incentive to sell one additional low fuel-economy vehicle and a greater incentive to sell high fuel-economy vehicles—it needs to shift its mix of vehicles to comply with the standard. In practice, therefore, the firm will sell high fuel-economy vehicles at a discount, below marginal cost if the firm is perfectly competitive, and will implicitly face a tax on low fuel-economy vehicles, requiring a price above the vehicle's marginal cost to sell one. Therefore, in response to the fuel-economy standard, the firm implicitly subsidizes high fuel-economy vehicles while implicitly taxing low fuel-economy vehicles.

There are several additional important features and consequences of fuel-economy standards. First, even though fuel-economy standards apply directly to new vehicles only, their impacts go beyond the new-car market. In particular, the change in new-car prices induced by the standards will affect used-car prices. This will, in turn, lead to changes in when vehicles are scrapped. High-fuel-economy used vehicles will become less valuable given that the new-car alternative has become cheaper, and they will be scrapped sooner because their resale value decreases. In contrast, low fuel-economy vehicles will stay on the road longer.

The second consequence of fuel-economy standards is that consumers are now driving more fuel-efficient vehicles than they otherwise would have chosen, whereas gasoline prices remain unchanged. This means that the cost per mile of driving has decreased, leading drivers to drive more. This effect is known as rebound.

There is a third issue that complicates estimating the costs and benefits of fuel-economy standards. It is possible that consumers systematically make mistakes when choosing vehicles. Specifically, some have claimed that consumers undervalue future fuel savings when investing in fuel economy. This, if true, would lead consumers to purchase the wrong vehicle for them. This effect is not an externality, a cost that is borne by others rather than the person making the vehicle choice, but is instead an internality. The presence of the internality implies that fuel-economy standards can improve societal welfare by improving consumer choices because high fuel-economy vehicles will be (implicitly) subsidized and low fuel-economy vehicles will be (implicitly) taxed. If, however, consumers correctly value fuel economy, absent the standard they would choose vehicles with a level of fuel economy that is privately optimal; imposing a standard can then only force them to deviate from this optimal choice, leading to a welfare loss.

These various effects strongly influence the costs and benefits of fuel-economy standards and must therefore be properly accounted for in regulatory impact analyses. In this paper, we develop a tractable analytical framework to examine the welfare effects of the cost and benefits of fuel-economy standards, and we apply it to examine the recent proposal to roll back fuel-economy standards by the Trump administration. We first focus on a simplified model that only considers the new-car market and use this to highlight three key channels of adjustments: First, the fuel-economy effect, defined by the direct welfare gain (or loss) from a marginal tightening of the standard. Whether this effect generates a source of welfare gain or loss depends on agents' valuations of the lifetime fuel savings resulting from a higher standard—a welfare gain requires the presence of an internality caused by undervaluation. Second, the mileage effect, which isolates the welfare loss resulting from the value of the environmental, congestion, and safety externalities associated with increased driving, because the cost per mile driven declines with the tighter standard. Third, the gasoline market effect, which isolates the welfare gain from reduced externalities related to fuel consumption.

When we generalize the framework to include multimarket interactions, allowing individuals to choose between new and used vehicles and scrap existing vehicles, we present results that allow us to bound the resulting size of the overall fleet and extent of scrappage induced by a fuel-economy standard. From a public policy perspective, this exercise is particularly useful because the magnitude of the externalities is directly linked with the overall size of the fleet. We rely on this bounding exercise as a starting point for examining the 2018 Notice of Proposed Rulemaking (NPRM) analysis of the proposed rollback of the fuel-economy standards (US DOT, NHTSA, and EPA 2018a).

Traditionally, the EPA and NHTSA have relied on models that are well equipped to map the marginal cost curves for different fuel-saving technologies but do not account for consumers' vehicle choices, the integration of new, used, and scrappage markets, and preexisting policies to reduce gasoline consumption. In practice, the agencies often attempt to get at some of these multimarket effects through somewhat ad hoc calculations. These analyses are often done in a piecemeal fashion, where prices in different parts of the model do not feed back into others. It is then possible for individual predictions to have the correct sign but for the combined model to generate counterintuitive outcomes. Bento et al. (2018) discuss the underlying assumptions behind the recent analysis for the rollback of the fuel-economy standard, pointing out where the analysis could benefit from a model that includes feedback effects across the affected markets. In particular, NHTSA's vehicle scrappage assumptions imply that CAFE standards increase the size of automobile fleet despite the fact that CAFE standards increase the average price of vehicles. This will overstate the gains from eliminating the standards.

Here we extend Bento et al. (2018) in two ways: first, by developing a simple analytical framework that provides useful checks on many of these ad hoc model integrations; second, by deriving bounds that offer insights into the magnitudes of potential errors that result from imperfect multimarket integration in the models used by the agencies and providing simple ways to attempt to fix them.

The rest of the paper is organized as follows. Section II presents the analytical framework to decompose sources of welfare change from a marginal increase in the fuel-economy standard and derives important bounds. Section III summarizes intuition for the sources of cost and benefit in the combined framework. Section IV shows how the bounds can be calculated in practice and illustrates their usefulness in the context of the 2018 proposal for the rollback of the standard. Section V offers some concluding remarks.

II. A Conceptual Framework for Evaluating the Costs and Benefits of Tightening CAFE Standards

In this section we present a framework to analyze the efficiency channels of adjustment under a marginal tightening of the CAFE standard and to shed light on the resulting categories of costs and benefits. We begin with the model in Fischer, Harrington, and Parry (2007), who consider the new-car market using a representative agent to capture average behavior of vehicle purchasers. All variables in the model are continuous rather than discrete, facilitating the exposition. In the simplest setting the standard is an overall average target for increased fuel economy, leading to three main channels of adjustment. Section II.C then expands the framework to describe a set of channels for efficiency loss that arise under footprint-based standards. Finally, in Section II.D we complete the framework with a set of results on equilibrium interactions between the new- and used-car markets (via scrappage decisions). This last component captures changes in the aggregate scale and age composition of the fleet, influencing the magnitude of the externalities associated with vehicle use. The three components together form a complete framework for analysis, with the combined intuition summarized in table 1.

A. *Basic Assumptions*

Representative Agent

Fischer et al. (2007) represent a static economy where a period denotes the life span of a new vehicle. They consider the behavior of a representative agent who derives utility from X, a general consumption good, and D, the private benefit from driving. D can be expressed as

$$D = D(v, m, \overline{H}, q), \tag{1}$$

where v denotes the number of vehicles purchased at the start of the period, m denotes vehicle miles traveled expressed as hundreds of miles driven per vehicle, and $\overline{H}$ represents government spending on highway maintenance and expansion. The bar denotes that the representative agent takes this as given. Finally, q is an index of vehicle attributes, such as horsepower, weight, and size; $D(.)$ is increasing in all its terms.

Automobile use generates external costs in the form of local and global pollution, traffic congestion, accidents and fatalities, and oil dependence; $E(.)$ will denote these external costs, which increase with overall vehicle miles $M = vm$ and overall gasoline consumption $G = gM$, with g representing gallons consumed per 100 miles.[1] External costs proportional to gasoline consumption include carbon emissions, oil dependency, and upstream emissions from the petroleum industry. External costs proportional to vehicle miles traveled include traffic congestion, accidents, and local tailpipe emissions.

The representative agent's utility function can then be expressed as[2]

$$U = u(D, X) - E(\overline{M}, \overline{G}). \tag{2}$$

where U represents the representative agent's total utility and u is the agent's utility from driving and the general consumption good only.

The representative agent faces a perceived budget constraint equal to

$$I + F = p_X X + (p_v + \Gamma)v, \tag{3}$$

where I represents private income and F represents a transfer payment from the government. The variables p_X, p_v, and Γ denote, respectively, the prices of the general good, the purchase price of the vehicle, and the lifetime operating costs per vehicle as perceived by the representative agent. Specifically, Γ is defined as

$$\Gamma = \rho(p_G + t_G)mg, \tag{4}$$

where p_G is the pretax retail price of gasoline, t_G is a tax per gallon of gasoline consumed, and g is gallons consumed per 100 miles. Fuel-economy standards have often been supported with the argument that agents underestimate the actual fuel-savings benefits they realize over the vehicle's lifetime from higher levels of fuel economy. When $\rho = 1$ the representative agent correctly values fuel costs, whereas when $\rho < 1$ the representative agent undervalues the actual savings from fuel-economy improvements. The empirical literature that provides estimates for ρ continues to evolve, with some studies (e.g., Leard, Linn, and Zhou 2018; Gillingham, Houde, and van Benthem 2019) suggesting substantial amounts of undervaluation, and other studies (e.g., Busse, Knittel, and Zettelmeyer 2013; Sallee, West, and Fan 2016) pointing to close to full valuation. Allcott and Wozny (2014) find modest amounts of undervaluation. To whatever extent agents value the lifetime savings that result from higher fuel economy, this is reflected in the vehicle purchase price.

In the absence of the fuel-economy standard, the representative agent chooses v, q, g, m, and X to maximize its utility, taking into consideration the budget constraint and accounting for the relation between vehicle prices, fuel economy, and other vehicle attributes. Note that Fischer et al. (2007) consider the perceived budget constraint, rather than the actual, allowing for reoptimization over X and m as the representative agent learns about actual fuel costs paid at the pump. Allowing for this reoptimization captures the idea that driving is an ongoing decision and requires forecasting over a long-run horizon. This contrasts with the one-time vehicle purchase decision.

Production: Automakers and Producers of Fuel and the Composite Good

Firms are competitive and produce vehicles, fuel, and the composite good with constant returns to scale production functions, yielding zero pure profits. Of course, when it comes to the modeling of automakers' behavior, others (Goldberg 1998; Austin and Dinan 2005; Bento et al. 2009; Jacobsen 2013a) incorporate product differentiation and allow for non-competitive vehicle purchase prices. From the perspective of our framework here, allowing for such features would primarily alter the split of the regulatory burden between the representative agent and the firms. More important, for the purpose of deriving tractable welfare formulas for the tightening of the standard, a more realistic representation of automakers' behavior would not alter the channels of adjustment induced by the standard.[3]

Under perfect competition, the price of a vehicle will be set such that

$$p_v = \hat{p}_v + C(\hat{g} - \bar{g}, \hat{q}), \tag{5}$$

where hatted variables represent baseline values in the absence of fuel-economy regulation; $C(.)$ is the resulting increase in the costs of producing the vehicle (relative to the baseline) from adopting fuel-saving technologies to bring the level of fuel economy to $\hat{g}$. Here, $\hat{g}$ denotes the level of the standard set by the government. It is important to recognize that, implicitly, the analysis begins from an equilibrium with no standard; $C(.)$ is assumed to be a convex function in $\hat{g} - \bar{g}$, for a given $\hat{q}$. The zero-profit equilibrium implies that

$$p_v - \hat{p}_v = C(\hat{g} - \bar{g}, \hat{q}). \tag{6}$$

The function $C(.)$ is general enough to capture the idea that technologies can be incorporated into vehicles to improve fuel economy and/or alter other vehicle attributes. In that sense, a higher $\hat{q}$ denotes more technologies being used to improve other vehicle attributes. The substitutability of technologies (in the sense that many technologies could be used to increase either $\hat{q}$ or $\hat{g}$) appears in that the marginal cost of meeting the fuel-economy standard is increasing in $\hat{q}$. Similarly, the marginal cost of improving $\hat{q}$ is increasing in the level of fuel economy. Intuitively, this positive cross-partial derivative in cost arises to the extent that there are competing uses of the same technologies.

Government

The government sets the level of fuel economy, $\bar{g}$, collects fuel tax revenues, transfers lump-sum funds to the representative agent, and invests in road maintenance and expansion. Government budgets must balance, so that when government revenues decline due to improvements in fuel economy, the reduction in fuel tax revenues can be offset by reductions in either H or F. In other words:

$$t_G G = H + F. \tag{7}$$

B. *The Welfare Effects of a Tightening of the Fuel-Economy Standards*

The welfare effect of a tightening of the fuel-economy standard, accounting for changes in external costs, can then be derived (see detail in Fischer et al. 2007) by differentiating the indirect utility function of the household and substituting in the changes in H or F needed to balance the government budget:

$$-\frac{1}{\lambda}\frac{dV(.)}{d\bar{g}} = \underbrace{\left[m\left((p_G + t_G) - C_{\hat{g}-\bar{g}}(\hat{q})\right)\right]v}_{\text{fuel economy}} - \underbrace{\frac{E_M}{\lambda}\left(-\frac{dM}{d\bar{g}}\right)}_{\text{mileage}} + \underbrace{\left(\mu t_G - \frac{E_G}{\lambda}\right)\left(-\frac{dG}{d\bar{g}}\right)}_{\text{gasoline}} \tag{8}$$

$$\begin{aligned}-\frac{dM}{d\bar{g}} &= -\left(v\frac{dm}{d\bar{g}} + m\frac{dv}{d\bar{g}}\right) > 0; -\frac{dG}{d\bar{g}} \\ &= \left(M + \bar{g}\frac{dM}{d\bar{g}}\right) < 0; \mu = \left(\frac{dF}{dG} + \frac{dH}{dG}\frac{(du/dH)}{\lambda}\right)\frac{1}{t_G},\end{aligned} \tag{9}$$

where λ denotes the marginal utility of income and $V(.)$ the indirect utility function; E_G/λ and E_M/λ are the marginal costs of externalities that are proportional to gasoline consumption and vehicle miles driven (measured in dollars per gallon and dollars per mile, respectively).

In equation (9), $-dM/d\bar{g}$ represents the so-called rebound effect from fuel-economy improvements—that is, the increase in vehicle miles traveled that results from the tightening of the fuel-economy standards. The rebound effect equals the increase in miles driven per vehicle times the number of vehicles net of the decline in miles that results from lower vehicle sales following the increases in the price of the vehicle; $-dG/d\bar{g}$

represents the overall change in gasoline consumption. It equals the direct fuel savings that result from the fuel-economy improvement, net of the rebound effect. The variable μ can be interpreted as the marginal value of government revenue and so multiplies the change in gasoline tax revenue resulting from the policy.

Equation (8) decomposes the key channels of efficiency that result from a marginal tightening of the fuel-economy standard. The first term denotes the fuel-economy effect. It represents the change in fuel economy and equals actual fuel-savings benefits that result from the standard less the increase in the vehicle price, times the number of vehicles. When consumers undervalue the lifetime benefits of fuel-economy savings, this effect will be positive, translating into a benefit. However, if agents fully value the lifetime benefits of fuel-economy savings, this effect becomes a welfare loss, because

$$C_{\hat{g}-\bar{g}} > m(p_G + t_G). \qquad (10)$$

In other words, the marginal cost from reducing fuel use per 100 miles exceeds the actual fuel-savings benefits, because the value of these fuel savings is correctly anticipated by consumers.

The second term denotes the mileage effect. This is the welfare loss that results from the externalities associated with increased miles driven that result from the tightened standard. One should, however, note that increases in miles driven due to the standard also translate into private benefits from additional mobility services, especially if individuals undervalue fuel-economy savings. In fact, the measurement of the costs and benefits in the 2016 and 2018 regulatory analyses considers this category of benefits.

Finally, the third term denotes the changes in welfare in the gasoline market (termed the gasoline effect). It equals the change in gasoline net of the marginal external costs of gasoline consumption. In general, the reduction in gasoline use that results from the tightening of the fuel-economy standard only generates a welfare gain if the preexisting gasoline tax does not fully charge consumers for fuel-related external costs. Typically, the value of the preexisting gasoline tax is substantially below the value of the external costs of fuel consumption. Therefore, the standard will likely generate large welfare gains through this channel of adjustment.

With this simple model, a tightening of the fuel-economy standard generates a welfare gain if the gasoline effect dominates the mileage effect, accounting for the fuel-economy effect (the sign of which depends on the degree of undervaluation of fuel economy by consumers). Together, these effects tend to represent a welfare gain if individuals undervalue lifetime fuel-economy savings or if external costs of driving are large. There will be a negative welfare effect if consumers fully value fuel savings, technology is expensive, or external costs are limited.

C. *From an Average Fuel-Economy Standard to a Footprint-Based Standard*

So far, the fuel-economy standard is modeled as an "average" rule. Such representation made the exposition above simpler, as the standard did not distort the space of vehicle attributes. The CAFE standards in the United States, however, are footprint-based standards and likely distort vehicle attributes. As a consequence of this structure, footprint-based standards will generate additional sources of welfare losses—both private and external—if, by manipulating attributes, automakers produce vehicles that depart from individuals' most desired products. In addition, the structure of the standard is likely to generate other external sources of welfare loss by exacerbating the level of preexisting externalities. Several studies examine the importance of distortions of vehicle attributes in this context: Whitefoot and Skerlos (2012) use engineering estimates of vehicle-design costs and a discrete-choice model to predict how automakers manipulate attributes related to footprint in response to the standard. Reynaert (2019) examines distortions under the European Union's weight-based standards. Finally, Jacobsen (2013b) addresses the safety impacts of footprint-based standards in the United States.

Ito and Sallee (2018) characterize the theoretical incentive that footprint-based standards create to distort the secondary attribute. In the context of the Japanese market, the authors show that vehicles experience a notable increase in weight in response to attribute-based regulation that requires less stringent fuel-economy targets as vehicles move to heavier weight bins. In turn, this weight increase exacerbates safety-related externalities (in general, heavier vehicles do more damage to other parties in accidents, much of which is not internalized).

D. *Multimarket Interactions: The Used-Car Market and Scrappage*

Each of the channels laid out above appears in the new-vehicle market. However, even though fuel-economy standards apply directly to new vehicles, they also indirectly affect the used fleet. In particular, standards for new vehicles increase new-car prices as new technologies are built into the vehicle (or reduce desirable attributes in the vector q, such as horsepower), in turn raising prices and reducing scrap rates among used cars. As a result, the used fleet will be larger than in absence of the standards.

To capture this effect, we divide the representative vehicle (v in the model above) into a new and used version, allowing individuals to choose between them. As demand (and price) of the used version rises in equilibrium, there will be an interaction between new and used markets via scrap decisions. The extent of that interaction allows us to bound the amount of scrappage induced by a fuel-economy standard, and so to bound the resulting size of the aggregate fleet.

In the context of the broader vehicle market, the increase in price and decline in the attractiveness of attributes operate like an implicit tax on new vehicles. This allows us to connect the model in Section II.B to theory developed in Jacobsen et al. (2019). We make the link by summarizing the decline in utility associated with a new vehicle into a term t_n, capturing both increases in cost $C(.)$ and reduced willingness to pay as attributes q become less desirable. As above, we continue to focus on equilibrium outcomes.[4]

The model considers a continuum of consumers indexed by i with quasilinear preferences over a numeraire c and new and used vehicles.[5] Each consumer maximizes their utility and chooses to buy a new vehicle (n), used vehicle (u), or no vehicle (o, for outside option). Consumers have heterogeneous preferences for newness, β_i, for example reflecting underlying differences in income or taste for attributes. This heterogeneity leads to equilibrium sorting into the choice of new, used, or no car.

A new car has marginal production cost k. We continue to assume competitive vehicle supply such that the new-vehicle price equals marginal cost: $p_n = k$. Used-vehicle supply in equilibrium will be determined by the quantity of new vehicles q_n multiplied by 1 minus the equilibrium scrap rate s. This relationship must hold in an equilibrium because it is not possible to create used cars without new ones (at least in a closed economy). The scrap rate is allowed to change as the used-vehicle resale price p_u changes.[6] Both the used-vehicle price and the scrap rate are determined endogenously in the model.

The function relating vehicle price and scrap rate can be microfounded by considering an underlying distribution of repair-cost shocks w. New vehicles are repaired and sold as used if and only if $w < p_u$. The repair-cost shock is realized at the end of the time period. Used cars are defined such that they are not ever repaired: their scrap rate is 100%. In this setting, the rental price of driving a used car r_u equals p_u. The rental price of driving a new car r_n equals the expected depreciation ($p_n - (1 - s)p_u$) plus expected repair costs $(1 - s)E[w|w < p_u]$.

Consumers split their income y between vehicles and other goods c.[7] The number of miles driven is kept exogenous but allowed to vary by age. Quasilinear preferences are then given generally as

$$u_i = c + \theta(\beta_i, j) \qquad \text{for} \qquad j \in \{n, u, o\}. \tag{11}$$

We normalize $\theta(\beta_i, o)$ (the vehicle portion of utility when no car is chosen) to zero and formalize the idea that β_i represents a taste for newness using $\theta'(\beta_i, n) > \theta'(\beta_i, u) > 0$. In words, the assumption on β_i is that all households get (at least some) utility from driving and that households with larger β_i get comparatively more utility from new cars. Note that the utility from driving, although positive, need not be larger than the cost of driving: in that case the household will sort itself into the outside option o.

Using this general utility function, households choose the car (or decide not to drive) that maximizes u_i. The following three results characterize the three channels of effects that a fuel-economy standard will have on the composition and scale of the fleet. Proofs appear in Jacobsen et al. (2019):

Result 1. $\partial q_n / \partial t_n < 0$.

Result 1 states that the equilibrium size of the new-car fleet shrinks when new vehicles become more expensive or otherwise less attractive. This is intuitive.

Result 2. $\partial \left(q_u / q_n \right) / \partial t_n > 0$.

Result 2 describes how the fleet-age composition changes as tightened fuel-economy standards put upward pressure on new-vehicle prices. As the price of used vehicles increases in equilibrium ($\partial r_u / \partial t_n > 0$), their owners are incentivized to scrap their vehicles at lower rates. Therefore, the long-run equilibrium share of used vehicles grows as new vehicles become less attractive. This is also referred to as the Gruenspecht effect (Gruenspecht 1982).[8] One could think of this phenomenon as a type of gasoline or emissions "leakage": the share of gasoline consumption occurring in the used fleet (relative to that in the new fleet) will rise compared with an unregulated market.

Result 3. $\partial q_o/\partial t_n > 0$.

Result 3 states that, as new vehicles become less attractive, the share of households choosing the outside good becomes larger and the overall number of vehicles declines. The general nature of the utility function means that the outside good can be thought of as including any noncar mode of transportation as well as avoided trips. Combining results 2 and 3, we note that although the share of used vehicles increases following an increase in the stringency of fuel-economy policy (result 2), the overall size of the vehicle fleet goes down (because the sum of new, used, and no car choices is a constant).

The logic is as follows: Result 1 simply states that tighter standards make new vehicles more expensive, and so fewer will be sold.[9] As a result, used vehicles—which are "produced" from new vehicles and avoided scrappage—will also become scarcer and thus more expensive in equilibrium. Because the prices of both new and used vehicles increase, both types of vehicles become less attractive.[10] Former car owners will leave the market, prompted by the more expensive used vehicles, more expensive new vehicles, or both. Hence, total fleet size decreases.[11]

How much smaller the fleet will be depends on the magnitude of the price changes and the aggregate elasticity to the outside good. In cities with well-developed public transit, for example, the fleet should shrink more than it would in rural areas where there may be limited outside options. Empirically, and specifically for the purpose of evaluating the costs and benefits of fuel-economy policies, the rate at which people switch from car ownership to the outside good when vehicle prices change is a crucial parameter. Unfortunately, to the best of our knowledge the academic literature provides little guidance on the magnitude of the aggregate elasticity to the outside good. We therefore see this as an important avenue of research for academic economists and government agencies alike.

III. Summarizing the Theory into Channels of Cost and Benefit under CAFE

The framework in Section II can be mapped into a specific set of channels for the realization of costs and benefits under CAFE. We provide that mapping in table 1 and then show in Section IV how certain channels can be bounded in practice using components of the underlying theory.

Table 1 is divided into three sections: the first two relate to private costs and benefits (e.g., in the utility to the consumer), and the third relates to changes in the magnitudes of externalities. Externalities include those realized among drivers (e.g., safety and congestion) and those imposed by drivers onto other parts of society (e.g., global and local air pollution). The center column shows where each particular channel appears in the theory model above. The final column provides intuition on the core mechanisms that will be relevant in the design and analysis of CAFE policy.

IV. Costs and Benefits in Practice

A. Demonstration of a Bounds Calculation for the Scrappage Effect

The theory in Section II.D gives us general bounds for the magnitude of the scrappage effect, which can in turn be mapped into changes in externalities connected to the size of the fleet. A full simulation of vehicle choice and scrappage would produce a point estimate of these effects; our bounds serve as a check on the theoretical consistency of such a simulation. These bounds can also be quite useful when a policy maker has limited information about vehicle choice and scrappage, as is the case with current models used by the EPA and NHTSA. These models do not explicitly consider consumer choices and typically do not integrate the new, used, and scrappage markets into an internally consistent multimarket model where all endogenous variables, including prices, adjust in response to the tightening of the standard. Therefore, having a simple method for deriving bounds becomes particularly important.

Table 2 demonstrates a method to map these bounds into limits on long-run leakage in gasoline use associated with changes in aggregate fleet size (results 2 and 3). The table focuses only on leakage via the used market; it does not include the rebound effect. We also show, by applying the same results, how the safety impacts associated with an aggregate shift toward older vehicles can be bounded.

Row 1 of table 2 contains an aggregate description of the fleet, approximately calibrated to the 2020 baseline laid out in the most recent CAFE rulemaking (US DOT, NHTSA, and EPA 2018a, b) as an example. We consider a policy that improves gasoline use per mile by 5% in the rows that follow. Five percent is approximately the improvement that would have been mandated under the Obama-era CAFE standards going from 2020 into 2021.

The key economic input needed in this exercise is the effect of regulation on new-vehicle sales, which determines the second column of the table. The attribute changes described in Section II, combined with elasticities from the literature, would be one way to model the change

Table 1
Linking Theory to Channels of Costs and Benefits

Channel	Theory Model	Key Aspects of Mechanism
Private costs:		
Vehicle price	Prices increase for both new (p_n) and used (p_u) vehicles	Both new and used options worsen from the perspective of the consumer, causing movement toward an outside "no car" option
Vehicle attributes	The attributes indexed in q worsen, utility per dollar of vehicle price falls	Two components should be considered: (i) reduction in horsepower and weight (part of optimization over convex technology costs), and (ii) misoptimized footprint (distorted upward via incentives in the standard)
Private benefits:		
Fuel savings	The gasoline effect in equation (8)	Savings can exceed the technology cost (price increase and attribute losses) if sufficient myopia is present on the part of the consumer
Mobility	The mileage effect in equation (8)	Notice that marginal miles driven will create significantly less net benefit than average miles driven (and zero net benefit if there are no preexisting distortions)
Externalities:		
Gasoline use	Proportional to the gasoline effect above	Fuel savings are reduced (relative to the simple improvement in fuel economy) by the rebound effect and amplified by the reduction in total fleet size
Local air pollution and congestion	Proportional to the mileage effect above	Ambiguous changes due to the rebound effect combined with reductions in fleet size
Safety	Combines three components: (i) The mileage effect in equation (8) (ii) Increases in the ratio of used to new vehicles in result 2 (iii) Changes in the attributes in q	Notes: (i) Accidents are roughly proportional to miles driven (holding ii and iii fixed) (ii) Older cars perform worse in accidents due to improved safety technologies in newer vintages (iii) The variation of size and weight in the fleet (especially relating to the potential for unmatched accidents of light with heavy cars) determines accident severity

Table 2
Demonstration of Bounds Calculation for Scrappage Effects

	Gallons per 100 Miles	New Vehicles (Million)	Used Vehicles (Million)	Total Fleet (Million)	Gasoline (Billion Gallons)	VMT (Billion)	Fatal Accidents (Low Differential)	Fatal Accidents (High Differential)
Baseline	4.0	18.0	232.0	250.0	100.0	2,500	23,000	23,000
No scrappage effect (theoretical lower bound)	3.8	17.9	230.5	248.4	94.4	2,484	22,851	22,851
Percentage change	–5.00	–.65	–.65	–.65	–5.62	–.65	–.65	–.65
Theoretical upper bound	3.8	17.9	232.1	250.0	95.0	2,500	23,004	23,005
Percentage change	–5.00	–.65	.05	.00	–5.00	.00	.02	.02
Estimate using scrappage effect from Jacobsen and van Benthem (2015)	3.8	17.9	231.0–231.3	248.9–249.2	94.6–94.7	2,489–2,492	22,898–22,930	22,899–22,931

Note: VMT = vehicle miles traveled.

in sales. Here we use a 0.65% decline in sales as an example; this again follows the recent rulemaking (see Gillingham, Stock, and Davis 2018).[12]

The third column displays the number of used vehicles in the fleet and therefore summarizes the scrappage effect: we construct lower and upper bounds on the used fleet using the results above. The "no scrappage effect" (lower bound) row shuts down the scrappage effect. It assumes that scrap rates remain fixed and so the 0.65% decline in sales translates exactly to a 0.65% decline in used cars over time. Notice that the gasoline savings increase from 5% (the mandated fuel-economy improvement per car) to 5.6% (adding in the effect of the shrinking fleet) given the fewer vehicles on the road. The theoretical upper bound on the scrappage effect is also straightforward to calculate: in this case all of the losses in new-car sales are compensated by reduced vehicle scrappage such that the fleet does not shrink at all in the steady state. It follows that gasoline savings at the upper bound are 5%.

The final two columns consider derived effects on vehicle safety (as measured by annual fatalities) at the lower and upper bound of the scrappage effect. These values capture a mixture of vehicle composition and scale and so require data on the relative safety of new versus used vehicles. We follow the NPRM for the proposed rollback from 2018 and use a 2018 US Department of Transportation (US DOT) report to assign differential risks by vehicle age (US DOT, NHTSA 2018; US DOT, NHTSA, and EPA 2018a). The "Low Differential" column assigns a 47% higher risk to used vehicles.[13] The "High Differential" column assigns nearly double the risk to used vehicles (this is the value cited in the 2018 NPRM: it compares the newest vehicles in the DOT report to those aged 18 years and older).[14] This produces a bound in two dimensions, in terms of the size of the scrappage effect and the assumption on differential risk. The results here are not sensitive to the specific assumption on differential accident risk: the final two columns are very similar despite a fairly large difference in the relative accident risk for used vehicles. We conclude that the age composition effects of the standards are relatively small; overall fleet-size effects are a stronger determinant of total accidents.

Specifically, we find that at the lower bound, when the fleet is shrinking, accidents shrink in proportion and the improvement in fuel economy is matched with 149 lives saved per year. At the upper bound the fleet does not shrink at all: the scrappage effect is so large that it entirely absorbs the reduction in new-car sales. Furthermore, the cars on the road are now older than they were before the CAFE policy. In the "high differential" case, these extra used vehicles are assumed to be nearly twice as likely to be involved in a fatal accident. The change in composition between new and used, plus the added risk in older vehicles, causes a modest increase of five fatalities per year at the upper bound.

The final row in table 2 displays an aggregate estimate of fleet and safety effects, in this case based on scrappage estimates from Jacobsen and van Benthem (2015). The key aspect to notice from a methodological standpoint is that the entire range of estimates falls within the two bounds identified above. Because the bounds represent the most extreme possible responses in scrappage (from no response in the used market at all to a complete replacement of lost sales), any calculation layered into this framework will necessarily fall between the two bounds. In this example, we see an aggregate fleet that shrinks by 0.8–1.1 million vehicles, with accident fatalities falling by between 69 and 102 per year. Hence, the slight positive change in fatalities in the second row, although technically possible because it lies on the upper bound, turns out not to be within the range of scrappage effects implied by Jacobsen and van Benthem (2015). An important caveat is that the simple analysis in table 2 is not accounting for changes in vehicle size and weight, which also enter fatality risk.[15]

The analysis for the final row of table 2 proceeds in the following steps. We begin by applying the upper bound (a complete replacement of lost sales) to the policy simulation in Jacobsen and van Benthem (2015). We start with their simulated fleet outcome for the central policy case, raising new-vehicle fuel economy by 5%. We then adjust the size of the long-run used fleet upward until it grows enough to completely replace lost sales. By construction, total fleet size is then the same in the baseline and the (upper bound) counterfactual outcome. We abstract from composition within different types and ages of used cars to match the present analysis.

This procedure leaves us with three different values for the fuel savings associated with a 5% fuel-economy improvement: (i) fuel savings in a counterfactual world where scrappage does not adjust at all (this is a lower bound on fleet size and therefore yields the highest gasoline savings), (ii) a new counterfactual world where scrappage adjusts to fully offset lost sales (this is the upper bound constructed above and produces the least gasoline savings), and (iii) the flexible policy cases where scrappage is endogenous following Jacobsen and van Benthem (2015).

Used-car leakage at the lower bound is zero by definition. Used-car leakage at the upper bound is calculated as 1 – (ii)/(i) and amounts to 32.8%. This maximum for used-car leakage is related to the fraction of fuel savings coming from the technological improvement versus the counterfactual change in fleet size in case (i). Much of the fuel savings, even in case (i), are coming from fuel-economy technology rather than the fleet, so even at the maximum leakage to the used fleet remains less than 100%.

Finally, we note that table 6 of Jacobsen and van Benthem (2015) reports a range of leakage in the policy cases varying between 10.2% and 17.1% when the scrap elasticity is varied between –0.5 and –1.0 (their central estimate is –0.7). Using a simple proportional back-of-the-envelope calculation, we find that this corresponds to leakage between 31% (10.2/32.8) and 52% (17.1/32.8) of the upper bound. Taking the 31%–52% range and applying it to the present setting (i.e., allowing the used-car fleet to adjust between 31% and 52% of the maximum in the upper bound in table 2) leads to the estimates on the last line.

B. *Application to the 2018 Proposal to Roll Back Fuel-Economy Standards*

We now highlight the relevance of the analytical framework and the bounding exercise presented above to the evaluation of the recent 2018 proposal for the rollback of the CAFE standards. In doing so, we draw heavily on recent work by Bento et al. (2018), who contrast the government analysis used to justify the increased 2022–25 standards (the 2016 technical assessment report; TAR) with the subsequent benefit-cost analysis that justifies rolling back these standards (the 2018 NPRM). The various categories of costs and benefits in these government analyses follow closely the costs and benefits outlined in table 1.

Table 3 presents the costs and benefits of imposing the stricter 2022–25 CAFE standards, relative to a world where the standards are frozen at model year 2020 levels through 2025 (the proposed rollback). The dollar values are as calculated by the agencies in their 2016 and 2018 analyses, respectively. This table relies exclusively on numbers reported in the two analyses. To calculate the impacts of a rollback (compared with a world where the more stringent standards stay in place), the costs become benefits (they are now avoided costs) and benefits become costs (they are now foregone benefits). The two analyses reach radically different conclusions. The 2016 analysis finds that moving forward with the stringent 2022–25 standard yields a net benefit of $87.6 billion, whereas the 2018 analysis finds a net loss of $176.3 billion.

Interestingly, in the 2018 analyses, total benefits are roughly twice as high as in the 2016 analysis, but the costs in 2018 increase by a factor of five. To understand what drives this stark result, we focus on three categories of modeling assumptions for the CAFE standards that determine

Table 3
Comparison of the Costs and Benefits of the CAFE Standards between the 2016 TAR and the 2018 NPRM

	2016 TAR (Billion 2016$)	2018 NPRM (Billion 2016$)
Costs:		
Vehicle technology costs	90.7	252.6
Noise and congestion	4.3	51.9
Rebound crash costs	1.8	106.8
Nonrebound crash costs	.0	90.7
Maintenance	5.2	.0
Total costs	102.0	502.0
Benefits:		
Pretax fuel savings	125.7	132.9
Energy security	9.3	10.9
CO_2 damages avoided	27.8	4.3
Non-GHG damages avoided	11.3	1.2
Refueling benefits	6.2	8.5
Rebound benefits	9.3	167.9
Total benefits	189.6	325.7
Total net benefits	87.6	–176.3

Sources: 2016 TAR, table 13.25, p. 1215 (US EPA, DOT, NHTSA, and California Air Resources Board 2016); 2018 NPRM, table VII-45, p. 652 (US DOT, NHTSA, and EPA 2018a).
Note: Costs and benefits from the TAR are in 2013$ and are converted to 2016$ with a 1.0303 conversion factor. See page 1000 in the 2016 TAR for a breakdown between rebound crash costs and noise and congestion costs. Note that the 2016 TAR evaluates an increase in stringency (reported above), whereas the 2018 NPRM evaluates a rollback (we count the estimated benefits of the rollback as being costs of increased stringency, and vice versa, to make the two columns above comparable). CAFE = Corporate Average Fuel Economy; TAR = technical assessment report; NPRM = Notice of Proposed Rulemaking; GHG = greenhouse gas.

their costs and benefits: the effect on miles driven per vehicle (rebound), the effect on the size and composition of the new and used-vehicle fleet, and the effect on technology and compliance costs. Finally, we discuss how the valuation of externalities has changed between the two analyses. The framework we develop above provides an intuitive check on the overall internal consistency of the models used by the agencies when computing the costs and benefits of the tightening of the standard.

The increase in overall benefits from the standards mostly results from a change in the assumed magnitude of the mileage effect (rebound effect)—under a more stringent standard, per-mile driving costs decrease due to higher fuel economy, and the amount of driving increases as a result. The mileage effect in equation (8) directly determines several of the most important costs of CAFE: exacerbated local pollution, congestion, and safety externalities. Increasing the rebound effect scales up these externalities, adding directly to the cost side of an analysis. The only benefit affected by rebound is the private mobility benefit from driving additional miles. As we note in table 1, this benefit will typically be quite small (the marginal miles driven will generate little surplus for the car owner as the most valuable miles in terms of mobility benefits will be driven anyway, with or without CAFE). Combining the two effects leads to costs dominating: a larger rebound effect tends to work against CAFE and in favor of a rollback.

The 2018 benefit-cost analysis uses a larger estimate of the rebound effect (20%) than the 2016 benefit-cost analysis (10%), despite recent evidence from the academic literature that finds smaller rebound effects. For example, West et al. (2017) find a 0% rebound effect; Langer, Maheshri, and Winston (2017) estimate a rebound effect of 11%; Knittel and Sandler (2018) find 14.7%; and Wenzel and Fujita (2018) estimate a range of 7.5%–15.9%. In the 2018 NPRM, the higher rebound effect of 20% leads to increased private driving benefits from the CAFE standard that are approximately equal to costs from the associated increase in accidents and pollution. Hence, the doubled rebound effect inflates both costs (e.g., more crashes) and benefits (more valuable trips) from CAFE standards by a factor of two. The valuation of driving benefits in the 2018 NPRM seems quite favorable in light of the discussion around table 1 above—even though the rebound effect is assumed to be large (working against a standard under which more miles are traveled per vehicle), the marginal trips that drivers add will likely generate limited surplus and not offset the increased externality costs directly associated with increased vehicle miles traveled as represented by the second term in equation (8) (neutralizing the first effect).

The second key driver of why the CAFE benefit-cost analyses differ lies in the modeling of the size and the composition of the new- and used-vehicle fleet. In Section II.D, we illustrated the importance of accounting for interactions between the new- and used-car markets and scrappage as standards increase. Effects in the used-car market, laid out in the results in Section II.D, enter prominently on the cost side of CAFE, as they determine the overall fleet size, fleet composition, and, as a consequence, the magnitude of all of the externalities.

The 2016 and the 2018 analyses model fleet effects in very different ways. Whereas the 2016 analysis mostly ignores interactions between the new and used fleet, the 2018 analysis makes an attempt to account for them. Our model is an attempt to improve on the NPRM analysis by capturing the multimarket nature of automobiles. As we have highlighted above in result 3, tighter standards make new vehicles more expensive, on average. This implies that, on average, used vehicles also become more expensive, because they are direct substitutes for new vehicles.[16] When the standard increases prices of both new and used vehicles, total fleet size should decrease over time. Conversely, a rollback should lead to increased demand for vehicles, resulting in a larger fleet that will be newer on average.

In sharp contrast to result 3, the 2018 analyses found that the rollback in standards will shrink the overall fleet by 6 million vehicles by the year 2029, compared with the current standards (Bento et al. 2018). As a result, the 2018 analysis concludes that the CAFE rollback will result in a $90.7 billion gain from reduced fatalities and property damages (see "Nonrebound crash costs" in table 3), a result driven almost exclusively by a 2.4% decrease in fleet-wide miles traveled due to the assumed decrease in the vehicle fleet. Changes in fleet composition play a minor role in the 2018 analysis. Using the intuition from the bounding exercise presented in Section IV.A, a theoretical lower bound on the change in fleet size under the rollback would be 0%, in which case the reported $90.7 billion gain from reduced fatalities would fall to near zero. The intermediate case suggested in our bounding illustration would result in the fleet size increasing following the rollback and turn the assumed gain into a potentially substantial loss, because economic theory actually predicts that the fleet will grow and, along with it, the external costs of the rollback.

The decrease in fleet size as a result of rolling back the standard in the 2018 NPRM can be explained by its lack of a vehicle-choice model that captures choices between cars of different ages, types, and attributes. As discussed in Section II.A, when consumers decide which car to buy, they trade off factors such as prices, fuel economy, and other vehicle attributes that determine the cost of vehicle ownership. In turn, this affects the consumer's willingness to pay for vehicles and the decision about how much to drive. Such a choice model should capture the interaction between new- and used-vehicle markets, as this is essential to consistently estimate the size and composition of the vehicle fleet and the prices of vehicles of different types and ages.

Rather than estimating fleet effects from a consumer choice model, the 2018 NPRM estimates the effect of the standard on the size of the used fleet in a rather ad hoc way. Whereas scrappage should result as an equilibrium outcome in a vehicle-choice model (as in Jacobsen and van

Benthem 2015 and Bento et al. 2018), the 2018 NPRM models it exogenously through a linear regression of scrap rates on new-vehicle prices, new-vehicle fuel costs, vehicle age, their lagged values, and some macroeconomic indicators (US DOT, NHTSA, and EPA 2018b). This analysis could be improved in two ways. First, the estimated relationship merely reflects correlations in the data but does not estimate a causal relationship that can be used for forecasting changes in scrap rates as a result of changing standards (a vehicle-choice model can). Second, the estimated relationship does not model scrap rates as a function of used-vehicle prices, which is what economic theory would suggest.

When equilibrium analysis is done piecemeal (not allowing prices in some parts of the model to feed back into others), it is possible for individual predictions to have the correct sign but for the combined model to generate results that are not theoretically consistent. In the case of the 2018 analysis, the scrappage effect has the correct sign (a rollback reduces used-vehicle prices, increasing scrap rates), but because this effect is not fed back into other pieces of the model (e.g., new-car sales and overall vehicle demand), the welfare effects are likely biased. In particular, the result from the 2018 analysis that the used-vehicle fleet will shrink by more than the new-vehicle fleet grows is incompatible with result 2 in Section II.D.

The third key determinant that drives the difference between the 2016 and 2018 benefit-cost analyses are the engineering technology cost estimates and other assumptions that determine the automakers' compliance cost with CAFE standards. An increase in technology cost directly reduces welfare from CAFE via equation (8)'s fuel-economy effect. Bento et al. (2018) discuss in detail reasons that lead to a fivefold increase in compliance costs in the 2018 versus the 2016 analysis. On the technology side, the 2018 NPRM removes some low-cost projected technology options, "forcing in" a perhaps unrealistically large amount of expensive hybrids and battery-electric vehicles. In addition, the projected costs of producing electric vehicles has increased by 20%–50% between the two regulatory analyses that were conducted only 2 years apart. In terms of other assumptions that affect the cost of compliance, the 2018 analysis ignores California's electric-vehicle mandate (which makes at least part of the increases in fuel economy required by the CAFE standards inframarginal) and ignores credit trading across fleets, automakers, and time, which is counterfactual to the current reality in which firms do have the ability to leverage such trading.

Finally, the 2018 analysis assumes much lower external damages from carbon emissions. This directly diminishes the external damage from gasoline use and therefore the benefits from tightening CAFE standards, this time via the gasoline effect in equation (8). The 2018 analysis accounts only for the domestic benefits from reducing carbon emissions but ignores benefits that accrue to other countries. Specifically, the 2018 NPRM values the social cost of carbon at $7.48 per ton of CO_2 in 2016 US dollars (US DOT, NHTSA, and EPA 2018b), whereas the 2016 analysis uses a global cost of carbon of $48.42 in 2016 US dollars (US EPA, DOT, NHTSA, and California Air Resources Board 2016). This change reduces the climate benefits of the CAFE standards by as much as 85%.

Taken together, a combination of differences in modeling assumptions and choices of parameter values drive the stark difference between the net benefits in the 2016 versus the 2018 benefit-cost analyses. The framework presented in this paper directly contradicts the fleet-size effects in the 2018 analysis and highlights how changes in the assumptions about technology costs and the social cost of carbon affect the overall net benefits of the policy. With regard to the chosen parameters themselves, the sharp increases in technology costs and the omission to model other compliance channels such as credit trading almost certainly lead to inflated costs attributed to the CAFE standards (Bento et al. 2018). The choice of a domestic rather than global cost of carbon stands in sharp contrast with common practice in government analysis, and—if applied by all countries individually—would fall far short of reaching the globally efficient amount of emissions.

Using a global social cost of carbon in combination with a highly conservative bound on changes to total fleet size closes 63% of the gap between the (negative) net benefits calculated and the "breakeven point" for the CAFE standard in the 2018 analysis: these changes alone would increase the net benefits from –$176 to –$64 billion. Given that, only modestly more optimistic technology assumptions, or accounting for alternative compliance channels that automakers have in practice, would yield positive net benefits of the original 2022–25 CAFE standards. These calculations highlight the need to apply an economically consistent framework for the evaluation of the costs and benefits of fuel-economy standards; this paper attempts to form a foundation for this.

V. Conclusions

In this paper we develop a tractable analytical framework to examine the welfare effects of the costs and benefits of fuel-economy standards. We decompose key sources of economic efficiency and highlight multimarket effects critical for recovering the overall fleet size, fleet composition, and vehicle miles traveled. These are essential to correctly recover the magnitude of the resulting externalities associated with vehicle use. Through an illustrative exercise, we also derive bounds that are useful for policy makers, especially when the models that the EPA and NHTSA use do not explicitly model consumer choices but rather rely on ad hoc mechanisms for integrating the new, used, and scrappage markets.

Endnotes

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1. A portion of travel costs and accident risks are internal to individual agents and implicitly incorporated in $D(.)$. Note the model assumes a fixed population and representative agent, so M and G may also be interpreted in per capita terms.
2. A bar denotes economy-wide variables that are exogenous to the representative agent.
3. However, if the standard has less impact on the representative agent, through a relatively lower price of the vehicle, it may have less impact in reducing the overall demand for vehicles and changing the composition of the fleet. We discuss these issues later in the text.
4. A range of possible transition dynamics could modify outcomes in the short run. Fully modeling this would require a rich array of interactions for which little empirical information is likely to be available.
5. The setting abstracts from income effects: to the extent vehicles behave as normal goods (which seems likely), we would expect fleet effects to be even more negative than in the results here.
6. Empirical estimates for the elasticity of scrappage with respect to used-vehicle price are available from Jacobsen and van Benthem (2015) and Bento et al. (2018).
7. The budget constraint then implies that c can be written as the residual: $c = y - r_j - t_j - fuel\_cost_j$.
8. In a model with multiple vehicle models with different fuel economies, the vehicles with the lowest fuel economy (conditional on footprint, in case of the US CAFE standards) will see their prices increase the most and their scrap rates go down the most. For such vehicles, manufacturers either need to make costly technological adjustments or substantially reduce their prices to affect the mix of vehicles sold.
9. As a side note, we mention that—in a setting with multiple vehicle models—a tighter standard does not necessarily translate to lower sales of every individual vehicle model. For example, hybrid sales are likely to go up even as sales of most other models go down. In theory, if consumers differ in how price sensitive they are and how they choose their vehicles, the effect on the total fleet size could be muted or exaggerated relative to the simple "representative vehicle" case. This, however, is beyond the level of sophistication in the extant academic literature.
10. Reductions in quality via the vector of attributes will have the same impact.
11. Note that the basic theory and intuition in this section, and specifically result 3, go counter to the arguments used by the US federal government in 2018 for rolling back the

increase in the MPG targets for the CAFE standards—the opposite of the case we study in this paper. In particular, the US EPA and NHTSA conclude that a rollback of the standards will result in a substantially smaller vehicle fleet, leading to fewer miles driven, fewer fatalities, and lower external costs and damages (Bento et al. 2018).

12. The model predicts an increase in price of 5%, so the implied price elasticity of (aggregate) demand is –0.13. In a full analysis it would be important try a range of elasticities. For example, longer-run elasticities in the 2018 government analysis are even smaller than this, whereas some vehicle-choice models (e.g., Jacobsen 2013a) imply larger aggregate demand elasticities. There is relatively little work in the academic literature that directly estimates this critical parameter.

13. The DOT report shows that 27% of occupants are killed in newer vehicles (conditional on a fatal accident) versus 39.8% across categories of older vehicles.

14. The DOT report indicates 50% of occupants are killed in vehicles aged 18 and above, producing a ratio between oldest and newest of 1.85.

15. Jacobsen (2013b) shows that variance in weight and size within the fleet (as opposed to changes in averages) determines nearly all of the overall risk; variance is not directly affected by CAFE.

16. Note that higher used-vehicle prices lead to lower scrap rates, but in equilibrium these lower scrap rates are applied to a lower vehicle stock. The net effect is a reduction in the used-vehicle fleet.

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