Estimating the Costs and Benefits of Fuel Economy Standards

Antonio M. Bento
University of Southern California and NBER

Mark R. Jacobsen
University of California at San Diego and NBER

Christopher R. Knittel
Massachusetts Institute of Technology and NBER

Arthur van Benthem
University of Pennsylvania and NBER

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1. Introduction

We develop a tractable analytical model to examine the welfare effects of the cost and benefits of fuel-economy standards, and apply it to examine the recent proposal to rollback fuel-economy standards by the Trump Administration. We first focus on an overly simplified model that only considers the new-car market, and use this model to introduce three key channels of adjustments: First, the *fuel-economy effect*, defined by the direct welfare gain (or loss) from the marginal tightening of the standard. Whether this effect generates a source of welfare gain or loss depends on agents' valuations of the lifetime savings resulting from a higher standard. Second, the *mileage effect*, which isolates the welfare loss resulting from the value of the externalities associated from increased driving, since 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 model to include multi-market interactions, allowing individuals to choose between new and used vehicles and scrap existing vehicles, we present useful results that allow us to bound the resulting size of the overall fleet and extent of scrappage. From a public policy perspective this exercise is particularly useful as the magnitude of the externalities are directly linked with the overall size of the fleet. We rely on this bounding exercise as a starting point for examining key flaws in the 2018 NPRM analysis of the proposed rollback of the fuel economy standards.

Traditionally, the EPA and NHTSA have relied on models that are well equipped to map the marginal cost curves for different technologies, but do not account for consumer choices, the integration of new, used, and scrappage markets, and pre-existing policies. In practice, these agencies often attempt to get at some of these multi-market effects through somewhat ad-hoc calculations. Due in part to many of these ad-hoc calculations, Bento et al (2018) documented well how flawed the recent analysis for the rollback of the fuel economy standard was due to several of these modeling inconsistences. Here we extend Bento et al (2018) in two ways: First, by developing a simple analytical model that provides useful checks on many of these ad-hoc model integrations. Second, by deriving bounds that offer insights on the magnitudes of potential errors that result from imperfect multi-market integration in the models used by the agencies, and provide simple ways to attempt to fix them.

The rest of the paper is organized as follows: Section 2 derives a simple analytical model to decompose the sources of welfare that result from a marginal increase in the fuel economy standard. We generalize this model by considering multi-market interactions in section 3 and derive important bounds. We illustrate the usefulness of these bounds in the context of the 2018 proposal for the rollback of the standard in section 4. Section 5 offers some concluding remarks.

2. A conceptual framework for evaluating the costs and benefits of tightening CAFE standards

In this section, we develop a tractable analytical model to inform the efficiency channels of adjustment exploited by a marginal tightening of the CAFE standard, and shed light on the resulting categories of costs and benefits. Building on Fischer et al. (2007), we start with a simplified model that only considers the new car market, with a representative agent that captures the average behavior of all new vehicle buyers in the economy. As a result, all variables in this model are continuous rather than discrete, facilitating the exposition. We first model the standard as a target for increased 'average' fuel economy, and then also consider a standard that is based on the footprint of the vehicles. Finally, we extend the model to consider interactions between the new and used car markets, and scrappage decisions. These are relevant for capturing the resulting overall size of the fleet in the economy and vehicle composition, which in turn affect the magnitude of the externalities associated with vehicle use.

A. Basic Assumptions

(a) Representative Agent

We represent a static economy where a period denotes the life span of a new vehicle. 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:

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

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 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. We assume that $D(.)$ 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; Let $E(.)$ denote these external costs, which increase with nationwide vehicle miles per capita $M = vm$ 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

[1] A portion of travel costs and accident risks are internal to individual agents, and implicitly incorporated in $D(.)$

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]

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

The representative agent faces a perceived budget constraint equal to:

(3) $I + F = p_X X + (p_v + \Gamma)v$

where I represents private income, and F represents a transfer payment from the government. 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, let Γ be equal to:

(4) $\Gamma = \rho(p_G + t_G)mg$

where p_G is the pre-tax 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 proposed with the argument that agents underestimate the actual fuel-savings benefits they realize over the vehicle lifetime from higher levels of fuel economy. When $\rho = 1$ the representative agent correctly values fuel costs, while 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 earlier studies (e.g. Alcott and Wozny, 2014) suggesting substantial amounts of undervaluation, and more recent studies (e.g. Busse et al., 2013; Sallee et al., 2016) pointing to close to full valuation. When agents fully value the lifetime savings that result from higher fuel economy, this valuation gets fully reflected in the vehicle purchasing price.

[2] A bar denotes economywide variables that are exogenous to the representative agent.

In the absence of the fuel economy standard, the representative agent chooses v, q, g, m and X to maximize the utility, taking into consideration the budget constraint and accounting for the relation between vehicle prices, fuel economy, and other vehicle attributes. Note that we considered the perceived budget constraint, rather than the actual, allowing for re-optimization over X and m as the representative agent learns about actual fuel costs paid at the pump. Allowing for this re-optimization 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.

(b) Production – Automakers and producers of fuel and the composite good

We assume that 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; and Jacobsen, 2013) incorporate product differentiation and allow for non-competitive vehicle purchasing prices. From our perspective, allowing for such features primarily alters the split of the regulatory burden between the representative agent and the firms. Efficiency could also be affected, but we would expect it to generate a relatively negligible effect. More importantly, 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 exploited by the standard.[3]

Retaining the assumption that automakers are perfectly competitive firms gives a price of a vehicle equal to:

[3] However, if the standard has less impact on the representative agent, through a relatively lower price of the vehicle, it may have a less impact in reducing the overall demand for vehicles, and changing the composition of the fleet. We discuss these issues in greater detail below.

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

Where ^ represents 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) that result from adopting fuel-saving technologies to bring the level of fuel economy to $\bar{g}$. Here $\bar{g}$ denotes the level of the standard set by the government. It is important to recognize that, implicitly, we are starting our analysis 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:

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

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, higher $\hat{q}$ denote more technologies being used to improve other vehicle attributes. As a consequence, the marginal cost of meeting the fuel economy standard is increasing in $\hat{q}$, reflecting the need to find other, more costly, technologies to improve fuel economy.

(c) *Government*

Government sets the level of fuel economy, $\bar{g}$, collects fuel tax revenues, and transfers funds to the representative agent and invests in road maintenance and expansion. We assume that government budget balances, so that when government revenues decline due to improvement in fuel economy, the reduction in fuel tax revenues can either be offset by reductions in H or F. In other words:

(7) $t_G G = H + F$

B. <u>The Welfare Effects of a tightening of the fuel economy standards</u>

The welfare effect of a tightening of the fuel economy standard, while accounting for changes in external costs can be expressed as:

$$\text{(8a)} \quad -\frac{1}{\lambda}\frac{dV(.)}{d\bar{g}} = \underbrace{\left[m\left((p_G + t_G) - C_{\hat{g}-\bar{g}}(\hat{q})\right)\right]v}_{Fuel\ Economy} - \underbrace{\frac{E_M}{\lambda}\left(-\frac{dM}{d\bar{g}}\right)}_{Mileage} + \underbrace{\left(\mu t_G - \frac{E_G}{\lambda}\right)\left(-\frac{dG}{d\bar{g}}\right)}_{Gasoline}$$

$$\text{(8b)} \quad -\frac{dM}{d\bar{g}} = -\left\{v\frac{dm}{d\bar{g}} + m\frac{dv}{d\bar{g}}\right\} > 0 \qquad -\frac{dG}{d\bar{g}} = \left\{M + \bar{g}\frac{dM}{d\bar{g}}\right\} < 0. \quad \mu = \left\{\frac{dF}{dG} + \frac{dH}{dG}\frac{u_H}{\lambda}\right\}\frac{1}{t_G}$$

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

In (8b) $-\frac{dM}{d\bar{g}}$ 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 increases in the price of the vehicle; $-\frac{dG}{d\bar{g}}$ represents the overall change in gasoline consumption. It equals the direct fuel savings that result from the fuel economy improved, net of the 'rebound effect'.

Equation (8a) 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 increased cost 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, since:

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

Or in other words, the marginal cost from reducing fuel per 100 miles exceeds the actual fuel-savings benefits, since the value of these fuel savings are correctly anticipated by consumers.

The second term denotes the ***Mileage Effect***. This is the welfare loss that results from the externalities associated with higher miles driven that result from the increased standard. One should, however, note that increases in miles due to the standard may also translate into private benefits, especially if individuals undervalue fuel economy savings. In fact, in the measurement of the costs and benefits in the 2016 and 2018 analyses, this category of benefits is considered.

Finally, the third term denotes the changes in welfare in the gasoline market. We term this the ***Gasoline Effect***. It equals the change in gasoline net of the marginal external costs of gasoline consumption. In general, the reduction in gasoline that results from the tightening of the fuel economy standard only generates a welfare gain if the pre-existing gasoline tax doesn't fully charge consumers for fuel-related external costs. Typically, the value of the pre-existing 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*, which could be a positive welfare gain if individuals undervalue the lifetime fuel economy savings, or a negative welfare effect if they fully value these savings.

C. From an average fuel economy standard to a footprint-based standard

So far, we have modeled the fuel economy standard as an 'average' fuel economy standard. Such representation made the exposition above simpler, as the standard did not distort the space of vehicle attributes. In practice, however, the standard is a footprint-based standard, and likely distorts vehicle attributes. For example, U.S. regulators chose the slope of the footprint-based standard in CAFE by fitting a line to data on fuel economy and footprint. As a consequence of the structure of the standard, footprint-based standards may generate additional sources of welfare losses – 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 pre-existing externalities. Recent studies examine the importance of these sources of welfare that result from distortions of vehicle attributes. For example, Whitefoot and Skerlos (2012) use engineering estimates of design costs and a discrete-choice model to predict how automakers manipulate attributes related to footprint in response to the standard. In the context of European standards, Reynart (2015) examined the E.U. standards which are weight-based. Finally, Jacobsen (2013b) addresses the safety impacts of footprint-based standards in the United States.

In recent work, 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. In turn, this weight increase exacerbates safety-related externalities (in general, added weight in a vehicle fleet will exacerbate pre-existing losses from the "arms race" that comes out of consumer choice).

D. Multi-market interactions: the used car market and scrappage

Section 2.B above shows how a CAFE standard imposes costs on new vehicles (as new technologies are built into the vehicle) and decreases their utility as a result of changing attributes in the vector q (for example by reducing horsepower, and increasing footprint, away from the original consumer's preferred choice of vehicle attributes). Here we divide the representative vehicle v into a new and used version and then consider the decision to maintain or scrap the vehicle over time.

The increase in price and decline in the attractiveness of attributes of new vehicles operates like an implicit tax. We summarize the decline in utility associated with a representative new vehicle in t_n: this measures increases in cost combined with reduced willingness to pay as attributes become less desirable. The drop in utility for new vehicles will reduce new vehicle sales and also have multi-market equilibrium effects that spill over into the used vehicle fleet. Both the composition and scale of the overall vehicle fleet can change. As with the changes in vehicle attributes discussed above, we continue to focus on equilibrium outcomes.[4]

In order to define and bound the channels for changes in the fleet we draw directly from theory developed in Jacobsen, Sallee, Shapiro and van Benthem (2019). They consider a continuum of consumers indexed by i with quasi-linear preferences over a numeraire c and new and used vehicles. 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.

[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.

A new car has marginal production cost m. We continue to assume competitive vehicle supply such that new vehicle price equals marginal cost: $p_n = m$. 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 since 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.[5] 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 micro-founded 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 $(1-s)\mathrm{E}[w|w < p_u]$.

Consumers split their income y between vehicles and other goods c.[6] The number of miles driven is kept exogenous but allowed to vary by age. Quasilinear preferences are then given generally as:

$$(10) \quad u_i = c + \theta(\beta_i, j) \text{ for } j \in \{n, u, o\}$$

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

[5] Empirical estimates for the elasticity of scrappage with respect to used vehicle price are available from Jacobsen and van Benthem (2015) and Bento, Roth and Zuo (2018).
[6] The budget constraint then implies that c can be written as the residual $c = y - r_j - t_j - fuel\_cost$.

with larger β_i get comparatively more utility from new cars. Note that the utility from driving, while 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. $\frac{\partial q_n}{\partial t_n} < 0$

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. $\frac{\partial \left(\frac{q_u}{q_n}\right)}{\partial t_n} > 0$

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 ($\frac{\partial r_u}{\partial t_n} > 0$), 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).[7] One could think of this phenomenon as a type of gasoline or emissions "leakage": the share of gasoline

[7] 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 U.S. 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.

consumption occurring in the used fleet (relative to that in the new fleet) will rise compared to an unregulated market.

Result 3. $\frac{\partial q_o}{\partial t_n} > 0$

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 non-car 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 (since the sum of new, used, and no car choices is a constant).

The logic is as follows: Result 1 states simply that tighter standards make new vehicles more expensive, and so fewer will be sold.[8] 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.[9] 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.[10]

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[8] As a side note, we mention that—in a setting with multiple vehicles 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.

[9] Reductions in quality via the vector of attributes will have the same impact.

[10] Note that the basic theory and intuition in this section, and specifically Result 3, go counter to the arguments used by the U.S. 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 U.S. EPA and NHTSA conclude that a rollback of

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.

3. Summarizing the theory into channels of cost and benefit under CAFE

The general model in Section 2 above can be mapped into a specific set of channels for the realization of costs and benefits under CAFE. We provide that mapping here in Table 1, and then show in Section 4 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 (coming out of the utility model for the consumer), and the third relates to changes in the magnitudes of externalities. Externalities include those realized among drivers (for example safety and congestion) and those imposed by drivers on other parts of society (for example, global and local air pollution). The center column shows where in the theory model above each particular

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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).

channel appears. The final column provides intuition on the core mechanisms that will be relevant in the design and analysis of CAFE policy.

4. Costs and benefits in practice

A. Demonstration of a bounds calculation for the scrappage effect

The theory in Section 2D 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 multi-market model, where all endogeneous variables, including prices, adjust in response to the tightening of the standard. Therefore, having a simple method for deriving bounds becomes particularly useful. Table 2 below demonstrates a method to map the bounds into leakage in gasoline use associated with changes in aggregate fleet size and safety impacts associated with the shift toward older vehicles (Results 2 and 3).

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 (DOT and EPA 2018a and 2018b) as an example. We consider a policy that improves gasoline use per mile by 5 percent in the rows that follow. 5% 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 2, combined with elasticities from the literature, would be one way to model the change in sales. Here we use a 0.65% decline in sales as an example; this again follows the recent rulemaking (see Gillingham et al 2018).[11]

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). 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 made up by reduced vehicle scrappage such that the fleet doesn't 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 composition and scale and so require data on the relative safety of new versus used vehicles. We follow the NPRM for the SAFE Act and use a 2018 DOT report to assign differential risks by

[11] 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 SAFE analysis are even smaller than this, while 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.

vehicle age.[12] 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 NPRM: it compares the newest vehicles in the DOT report to those aged 18+).[14] This produces a bound in two dimensions, in terms of the size of the scrappage effect, and the assumption on differential risk.

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. At the upper bound the fleet doesn't 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, and added risk in older vehicles, causes an increase of 5 fatalities per year at the upper bound.

The final policy case in Table 2 looks at an intermediate location between the two bounds: the choice of 42% comes from simulation results in Jacobsen and van Benthem (2015), though of course different modeling assumptions would lead to different points between the two bounds. That study reports a (central case) estimate of 13% leakage in gasoline savings due to scrappage

[12] Passenger Vehicle Occupant Injury Severity by Vehicle Age and Model Year in Fatal Crashes, Traffic Safety Facts Research Note, DOT HS 812 528. Washington, DC: National Highway Traffic Safety Administration. April 2018.

[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+, producing a ratio between oldest and newest of 1.85.

effects. By applying the upper bound to that baseline we arrive at 31% as the maximum leakage theoretically possible in their model (13/31=0.42).[15]

The implications for gasoline use and accident fatalities are linear between the bounds: in the intermediate estimates in the final row gasoline use would fall 5.4% and accident fatalities would be reduced by 85 per year. An important caveat is that the simple analysis in the table is not accounting for changes in vehicle size and weight, which also enter fatality risk.[16]

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 2022-2025 standards (the 2016 technical assessment report; TAR) with the subsequent benefit-cost analysis that justifies rolling back these standards (the 2018 Notice of Proposed Rulemaking; NPRM). The various categories of cost and benefits in these government analyses follow closely the costs and benefits outlined in Table 1.

Table 3 presents the costs and benefits of the 2022-2025 CAFE standards, relative to the proposed rollback levels as calculated by the agencies in their 2016 and 2018 analyses, respectively. This table relies exclusively on numbers reported in the two analyses. To evaluate the proposed rollback, one should simply change the signs of all costs and benefits. The two

[15] We apply the theoretical result by constructing a fleet (starting with the same baseline) where scrappage falls so much due to the policy that the overall fleet size is restored to the baseline level. This produces leakage of 31%. We note this abstracts from composition within different types of used cars; to match the present analysis we focus only on the new-used distinction.
[16] 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.

analyses reach radically different conclusions. The 2016 analysis finds that moving forward with the 2022-2025 standard yields a net benefit of \$87.6 billion, while 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 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 developed in previous sections will now provide 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 result 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 (8a) 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 mile driven will generate little surplus for the consumer 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 et al. (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, this higher rebound effect 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 both inflates 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 in favor of a rollback), the marginal trips that drivers add will likely generate limited surplus and not offset the increased externality costs (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 2.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 2.D, enter prominently on the cost side of CAFE, as they will 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. While the 2016 analysis mostly ignores interactions between the new and used fleet, the 2018 analysis makes an attempt to account for them but does so in an economically inconsistent manner. 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, since they are direct substitutes for new vehicles. When the standard increases vehicle prices, 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 in the year 2029, compared to 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 “non-rebound crash cost” in Table 3 above), 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 4.A above, 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, since economic theory actually predicts that the fleet will grow.

The inconsistencies in the overall outcomes of the fleet effects in the 2018 NRPM 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 2.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 effect 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, lagged values, and some macroeconomic indicators (PRIA, 2018). This is problematic for several reasons. 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 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 turn out to be inconsistent with theory. 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.

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 (8a)'s *fuel economy* effect. Bento et al. (2018) discuss in detail reasons that lead to this five-fold increase in compliance costs. 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%. 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 infra-marginal) 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 (8a). 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 U.S. dollars (PRIA, 2018), whereas the 2016 analysis uses a global cost of carbon of $48.42 in 2016 U.S. dollars (TAR, 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 for parameter values drive the stark difference between the net benefits in the 2016 vs. 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 2022-2025 CAFE standards. These calculation highlight the need to apply an economically consistent framework to the evaluation of the costs and benefits of fuel-economy standards; this paper attempts to form a foundation for this.

5. Conclusions

In this paper we develop a tractable analytical model to examine the welfare effects of the cost and benefits of fuel-economy standards. The analytical model decomposes key sources of efficiency, and highlights multi-market 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 which are useful for policymakers, especially when the models that the EPA and NHTSA use do not explicitly model consumer choices and rely on ad-hoc mechanisms for integrating the new, used and scrappage markets.

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Table 1: Linking Theory to Channels of Cost and Benefit

Channel	Theory model	Key aspects of mechanism
Private costs		
Vehicle price	Prices increase for both new (p_n) and used (p_u)	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) Mis-optimized 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 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 pre-existing 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 total mileage effect above	Ambiguous changes due to the rebound effect combined with reductions in fleet size
Safety	Combines 3 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 mixture of size and weight attributes in the fleet (especially relating to the potential for mismatched accidents) determine accident severity

Table 2: Demonstration of Bounds Calculation for Scrappage Effects

	Gallons per 100 miles	New vehicles (million)	Used vehicles	Total fleet	Gasoline (billion gals)	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
Policy to raise fuel economy by 5%								
No scrappage effect (lower bound)	3.8	17.9	230.5	248.4	94.4	2,484	22,851	22,851
% change	-5.00	-0.65	-0.65	-0.65	-5.62	-0.65	-0.65	-0.65
Theoretical upper bound	3.8	17.9	232.1	250.0	95.0	2,500	23,004	23,005
% change	-5.00	-0.65	0.05	0.00	-5.00	0.00	0.02	0.02
Intermediate (42% of upper bound)	3.8	17.9	231.2	249.1	94.6	2,491	22,915	22,915
% change	-5.00	-0.65	-0.36	-0.38	-5.36	-0.38	-0.37	-0.37

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

Benefits and Costs of Raising Standards		
	2016 TAR	*2018 NPRM*
	Billion 2016$	*Billion 2016$*
	(1)	(2)
Costs		
Vehicle Technology Costs	$90.7	$252.6
Noise and Congestion	$4.3	$51.9
Rebound Crash Costs	$1.8	$106.8
Non-Rebound Crash Costs	$0.0	$90.7
Maintenance	$5.2	$0.0
Total Costs	**$102.0**	**$502.0**
Benefits		
Pre-Tax Fuel Savings	$125.7	$132.9
Energy Security	$9.3	$10.9
CO2 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 for CAFE standards: 2016 TAR, Table 13.25, p. 1215; 2018 NPRM, Table VII-45, p. 652.

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.