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Should Automobile Fuel Economy Standards Be Tightened?

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Abstract

This paper develops analytical and numerical models to explain and estimate the welfare effects of raising Corporate Average Fuel Economy (CAFE) standards for new passenger vehicles. The analysis encompasses a wide range of scenarios concerning consumers' valuation of fuel economy and the full economic costs of adopting fuel-saving technologies. It also accounts for, and improves estimates of, CAFE's impact on externalities from local and global pollution, oil dependence, traffic congestion, and accidents. The bottom line is that it is difficult to make an airtight case either for or against tightening CAFE on pure efficiency grounds, as the magnitude and direction of the welfare change varies across different, plausible scenarios.

Key Words: fuel economy standards, oil dependency, carbon emissions, rebound effect, gasoline tax

JEL Classification Numbers: R48, Q48, H23

Contents

1. INTRODUCTION 1

2. MODEL DESCRIPTIONS 4
  2.1. Single-Vehicle Model 4
  2.2. Multi-Vehicle Model 8

3. PARAMETER VALUES 10
  3.1. Basic Vehicle Data 10
  3.2. Perceived Fuel Economy Benefits and Technology Adoption to Enhance Other Attributes 11
  3.3. Vehicle Demand and Mileage Elasticities 11
  3.4. Local Pollution Costs 12
  3.5. Global Pollution Costs 13
  3.6. Congestion Costs 13
  3.7. External Accident Costs 14
  3.8. External Costs of Oil Dependence 15
  3.9. Government Parameters 16

4. RESULTS 16
  4.1. Single-Vehicle Model 16
  4.2. Multi-Vehicle Model 18
  4.3. Should CAFE Standards Be Tightened? 19

5. CONCLUSION 19

REFERENCES 20

APPENDIX A: ANALYTICAL DERIVATIONS 23

APPENDIX B: SOME DETAILS ON MODEL CALIBRATION 24
  Adjusting own-price vehicle elasticities from the GM model 24
  Own-price vehicle elasticity in the single-vehicle model 24
  Estimating external accident costs 25

FIGURES AND TABLES 26

SHOULD AUTOMOBILE FUEL ECONOMY STANDARDS BE TIGHTENED?

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1. INTRODUCTION

The Corporate Average Fuel Economy (CAFE) program requires automobile manufacturers to meet standards for the average fuel economy of their passenger vehicle fleets; these standards are currently 27.5 miles per gallon (mpg) for cars and 22.2 mpg for light-duty trucks (SUVs, minivans and pickups). Proponents of raising CAFE standards emphasize two rationales. First, higher standards can reduce greenhouse gas emissions and lessen the economy's dependence on a world oil market subject to volatility and political manipulation. Second, it is suggested that consumers may undervalue fuel economy and therefore that standards need to be tightened over time to ensure that emerging, cost-effective fuel-saving technologies are adopted (Greene 1998). In fact, the average fuel economy of the new passenger vehicle fleet is still below its peak in 1987 due to the rising share of light-duty trucks, which now account for half of new passenger vehicle sales (Figure 1).

Broad taxes on all oil products and carbon emissions are the most cost-effective policies to address energy security and climate change, as they exploit conservation options across all sectors, rather than just passenger vehicles; in fact, gasoline accounts for under half of nationwide oil consumption and only a fifth of carbon emissions (EIA 2002, Tables 5.11 and 12.3). But if a sector-by-sector approach is to

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be taken, rather than a more preferable, nationwide approach, then the more relevant comparison is between CAFE and an increase in the federal gasoline tax.

Higher fuel taxes would (strongly) improve welfare by deterring vehicle use and reducing traffic congestion, accidents, and local pollution, in addition to reducing carbon emissions and oil dependence; moreover, accounting for the efficient balance between fuel taxes and other taxes in financing the government's budget further strengthens the efficiency rationale for higher fuel taxes (Parry and Small 2005; Parry 2007; West and Williams 2007). Studies that compare fuel taxes with CAFE standards find that the latter are far less cost-effective at reducing gasoline, one reason being that, by lowering fuel costs per mile driven, they (slightly) increase, rather than reduce, vehicle use (Kleit 2004; Austin and Dinan 2005; West and Williams 2005, Parry 2007). Some analysts view these studies as not entirely fair, as they assume consumers correctly value view fuel economy and thereby rule out one of the main arguments for CAFE (Gerard and Lave 2003).

Even though CAFE might be well down many economists' hierarchy of ideal climate and energy security policies, it is still important to have a clear conceptual and empirical understanding of the welfare effects of CAFE, given the pervasive attention it receives in Congress and the popular press. Several studies have estimated the welfare effects of binding CAFE standards using competitive models of the new vehicle market and assumptions about technological possibilities for raising fuel economy, leaving aside externalities (e.g., Yee 1991; Thorpe 1997; Greene and Hopson 2003). These studies reach different conclusions about the sign of the welfare effect, depending on whether they assume cost-effective technologies would be adopted by the market or not.

Two recent studies, by Kleit (2004) and Austin and Dinan (2005), have received particular attention. Both analyses assume adoption of all cost-effective technologies; for example, Austin and Dinan (2005) emphasize that emerging fuel-saving technologies might have greater value if used instead to enhance other vehicle attributes, such as horsepower. Kleit (2004) puts the long-run annual cost of reducing gasoline demand by 7 percent under binding fuel economy regulation at $4 billion, while Austin and Dinan (2005) put the cost of a 10 percent reduction in gasoline demand at around $3 billion. Both studies comment on CAFE's impact on externalities; for example, Kleit (2004) suggests that the carbon and oil dependency benefits from reduced fuel consumption are outweighed by additional congestion and accident externalities, as people use fuel-efficient vehicles more intensively.

Although these earlier studies make very valuable contributions, this paper further contributes to the literature in three main respects. First, we integrate both market-failure arguments for CAFE; prior studies have discussed either externalities or possible undervaluation of fuel economy, but not both together within a single framework. While we do not necessarily endorse the "undervaluation" hypothesis ourselves, many other respected analysts do; it is therefore useful to demonstrate how much undervaluation would be necessary for higher standards to significantly improve overall welfare under different scenarios for externalities and the costs of regulatory compliance.

Second, we develop improved quantitative estimates of CAFE's impact on a number of externalities including local pollution, congestion and accidents. We also integrate fuel taxes, which partly charge motorists for external costs in higher fuel prices.

Third, we develop both an analytical model with just one type of vehicle, and a multi-vehicle model, solved numerically, that incorporates changes in vehicle-fleet composition, differences in external costs across vehicles, and differential standards for cars and light trucks. The single-vehicle model provides a simple formula for welfare effects that is easy to implement and that provides an approximate prediction of welfare effects from the multi-vehicle model; however the latter model provides additional insight and a richer policy simulation.

The bottom line is that the efficiency rationale for raising fuel economy standards appears to be weak, unless carbon and oil dependency externalities are far greater than mainstream economic estimates, or consumers perceive only about a third of the fuel-saving benefits from improved fuel economy. But there are two important caveats. One is that even if neither condition is applicable, the downside welfare losses from tightening CAFE may not be large. Much depends on whether, without policy change, emerging technologies would be incorporated to enhance other vehicle attributes or to improve fuel economy—it is very difficult to project, ex ante, which of these scenarios is the more likely. The other caveat is that we omit some benefits of reducing oil dependence that have not been quantified, such as possible geopolitical benefits from reduced reliance on oil from unstable regions. Although it can be argued both ways, if the only practical options at present were to gradually tighten CAFE over time or take no action to cut carbon or oil use, we would lean toward the former, even though this position cannot be defended by a compelling efficiency analysis. That said, legislation ideally would specify a suspension of the progressive tightening of fuel economy if carbon or broader energy taxes were phased in down the road, as that would help to address the possibility that action on fuel economy standards might reduce pressure for other, more effective and efficient policies.

The rest of the paper is organized as follows. Section 2 describes the single- and multi-vehicle models. Section 3 discusses parameter values. Section 4 discusses the main results, sensitivity analysis, and our interpretation of the policy implications. The final section discusses additional caveats to the analysis.

2. MODEL DESCRIPTIONS

2.1. Single-Vehicle Model

Preferences. Consider a static model where a period represents the life span of a new passenger vehicle (about 14 years). An agent, representing an average over all new vehicle buyers in the real economy, has utility:

$$(1) \qquad U = u(D, X) - E(\overline{M}, \overline{G}), \qquad D = D(v, m, \overline{H}, q).$$

Variables are expressed in per-capita terms, a bar denotes an economywide variable that is exogenous to individual agents, and X is a general consumption good.

$D(.)$ is the private benefit from auto travel, which is increasing in the number of vehicles purchased at the start of the period v, vehicle usage during the period m, expressed as hundreds of miles driven per vehicle, government spending on highway expansion and maintenance H, and an index of (non-fuel economy) vehicle attributes, such as power, comfort, safety, and payload, denoted q. Given that all these variables, including the vehicle choice, are economywide averages, they are continuous rather than discrete.

E is an index of external costs from automobile use representing local and global pollution, traffic congestion, traffic accidents, and oil dependence; E increases with nationwide vehicle miles per capita $M = vm$ and with gasoline consumption $G = gM$, where g is gallons consumed per 100 miles. Travel time costs and accident risks that are internal to individual agents (as opposed to costs that individuals impose on others) are implicitly incorporated in $D(.)$.

We define:

$$(2) \qquad \Gamma = \rho(p_G + t_G)mg,$$

where p_G is the pre-tax retail gasoline price and t_G is a specific tax per gallon. Γ is lifetime fuel costs per vehicle, as perceived by agents at the start of the period. If $\rho = 1$, agents are "far-sighted" and correctly value fuel costs. If $\rho < 1$, agents are "myopic" and discount fuel costs by an excessive amount; therefore they will underestimate the actual fuel-saving benefits they receive over the vehicle life from higher fuel economy. While some economists are dismissive of this undervaluation hypothesis, other analysts believe that consumers only consider the first few years of savings rather than lifetime savings, pay little attention to fuel economy as they are more concerned with other vehicle attributes, or do not expect fuel economy to be fully reflected in used car prices.

Technology. Firms are competitive and produce vehicles, fuel, and the general consumption good under constant returns with zero pure profits.[1] The price of a new vehicle is determined by:

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

where ^ denotes a baseline value that would occur in the current period with no fuel economy regulation. *C*(.) is the increase in vehicle production cost over the baseline value, due to the incorporation of fuel-saving technologies to lower the fuel consumption rate to $\bar{g}$, the maximum (binding) standard set by the government.[2] *C*(.) is a convex function of $\hat{g} - \bar{g}$ (for given $\hat{q}$), and the zero-profit equilibrium implies $p_v - \hat{p}_v = C(\hat{g} - \bar{g}, \hat{q})$.

In the baseline, technologies emerging at the start of the period may be incorporated into new vehicles to improve fuel economy and/or enhance other vehicle attributes. The greater is $\hat{q}$—that is, the more these technologies are used to improve other attributes—the greater the (marginal) cost of meeting the fuel economy standard ($\partial C_{\hat{g}-\bar{g}} / \partial \hat{q}$ >0); this reflects the need to find other (more costly) technologies to improve fuel economy.[3]

Government. The government's budget constraint is:

(4) $$H + F = t_G G,$$

where *F* is a transfer payment from the government to households. We consider cases where reductions in fuel tax revenues (caused by the impact of regulation on gasoline demand) are offset by reductions in either *H* or *F*. We also assume the fuel tax rate is given. In practice, higher fuel economy may increase the pressure for a future increase in the fuel tax rate (see Section 5).

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[1] Austin and Dinan (2005) follow Goldberg (1998) by incorporating product differentiation and non-competitive vehicle pricing; consequently, part of the burden of regulatory compliance comes at the expense of producer surplus, rather than being entirely passed forward to consumers in higher vehicle prices. In this regard, fuel economy regulation has less impact on reducing the overall demand for vehicles, and changing the composition of the fleet, in their model than in ours; nonetheless, these effects only play a minor role in overall welfare impacts (see below).

[2] As in most other studies (Kleit 2004 is an exception), we ignore the possibility that the new standard is imposed on top of an existing, binding standard; in this regard, we may understate efficiency costs. Our assumption seems a reasonable approximation, however, given the recent rise in fuel prices and the fact that the car standard has been unaltered since 1985 (see Small and Van Dender 2006 for more analysis of this).

[3] Alternatively, we could assume that technologies to save fuel partly displace improvements in other vehicle attributes that would otherwise occur. However, this alternative formulation would be equivalent because of the envelope condition; that is, at the margin, the costs of reducing fuel through either incorporating additional technologies or diverting technologies that would otherwise have improved other attributes are equalized.

Baseline Equilibrium. At the start of the period, agents face the (perceived) budget constraint $I + F = p_X X + (p_v + \Gamma)v$, where *I* is private income and p_X is the price of the general good. In the baseline with no regulation, agents choose *v*, *q*, *g* and planned *X* and *m*, to maximize utility subject to this constraint, accounting for the relation between vehicle price, fuel economy, and other vehicle attributes. During the course of the period, they may re-optimize over *X* and *m*, based on actual (rather than projected) fuel costs paid at the pump.[4] This optimization yields:

(5a) $u_v / \lambda = p_v + \Gamma$

(5b) $u_m /(v\lambda) = (p_G + t_G)g$

(5c) $u_{\hat{q}} /(v\lambda) = C_{\hat{q}}$

(5d) $\rho(p_G + t_G)m = -C_{\hat{g}}$,

where λ is the marginal utility of income. In (5a-c), agents equate the private (monetized) benefit from an extra vehicle with the vehicle price and the perceived lifetime fuel cost, the private benefit from additional mileage per vehicle with the extra fuel cost per mile and the marginal benefit from other vehicle attributes with the incremental cost to vehicle production from enhancing those attributes. In (5d), the perceived fuel-saving benefits over the vehicle life from an incremental reduction in the fuel consumption rate is equated with the incremental cost to vehicle production. Binding fuel economy regulation violates this last condition, by reducing the fuel consumption rate past the point at which marginal private benefits and costs are equated, thus:

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

Welfare Effects. The welfare effect from an incremental reduction in $\bar{g}$ can be obtained by differentiating the agent's indirect utility function, accounting for changes in external costs, and in *F* or *H* to maintain government budget balance. The result can be expressed as the sum of three components (see Appendix):

(7a) $$\overbrace{\left(\mu t_G - \frac{E_G}{\lambda}\right)\left(-\frac{dG}{d\bar{g}}\right)}^{\textit{gasoline reduction}} - \overbrace{\frac{E_M}{\lambda}\left(-\frac{dM}{d\bar{g}}\right)}^{\textit{mileage increase}} + \overbrace{\{m(p_G + t_G) - C_{\hat{g}-\bar{g}}(\hat{q})\}v}^{\textit{fuel economy}}$$

(7b) $$-\frac{dM}{d\bar{g}} = -\left\{v\frac{dm}{d\bar{g}} + m\frac{dv}{d\bar{g}}\right\} > 0, \qquad -\frac{dG}{d\bar{g}} = \left\{M + \bar{g}\frac{dM}{d\bar{g}}\right\} < 0, \qquad \mu = \left\{\frac{dF}{dG} + \frac{dH}{dG}\frac{u_H}{\lambda}\right\}\frac{1}{t_G}.$$

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[4] This is reasonable because driving is an ongoing decision, unlike the one-off vehicle purchase, which requires forecasting over a long horizon.

E_G/λ and E_M/λ are the marginal costs of externalities that are proportional to gasoline consumption and vehicle miles, in \$/gallon and \$/mile respectively. As discussed below, the former includes carbon emissions, oil dependency, and upstream emissions leakage from the petroleum industry, while the latter includes traffic congestion, accidents, and local tailpipe emissions.

In (7b) $-dM/d\bar{g}$ is the increase in vehicle miles from a marginal reduction in the fuel consumption rate; it equals the number of vehicles times the increase in miles per vehicle in response to improved fuel economy, less a (partially) offsetting effect as regulation increases vehicle prices thereby causing a decline in the demand for vehicles (see below). $-dG/d\bar{g}$ is the change in gasoline consumption; it equals fuel savings on existing mileage from a unit reduction in *g*, less the "rebound effect"—that is, the extra fuel consumption from the increase in vehicle miles traveled. And μ is the marginal social benefit per dollar of tax revenue; if marginal revenue finances transfer payments, $dF/dG = t_G$ (from differentiating (5)) and $\mu = 1$, while if it finances highway spending, $\mu = u_H/\lambda$.

The first component in (7a) is the welfare change in the gasoline market; it equals the change in gasoline times the gasoline tax, scaled by μ, less the marginal external cost of gasoline consumption. If $\mu = 1$, highway spending fixed, and at the margin the fuel tax acts as an externality-correcting tax that incorporates some of the external costs of driving in the fuel price paid by motorists. In this case, the reduction in gasoline increases welfare only if the gasoline tax undercharges for fuel-related external costs.

If $\mu = u_H/\lambda$, the gasoline tax is effectively a user fee, as revenues are earmarked for highway spending. Suppose $u_H/\lambda > 1$, then the loss of gasoline tax revenue from reduced gasoline consumption produces a larger efficiency loss than in the case when marginal revenues finance transfer payments. This is because it now crowds out highway spending for which the social benefit per dollar of extra spending exceeds a dollar. Although the reduced spending will likely exacerbate road congestion, this possibility is taken into account in empirical studies of the return to highway spending that we use in choosing a range of values for u_H/λ.

The second component in (7a) is a welfare loss equal to the increase in vehicle miles times the marginal external cost of mileage-related externalities.

The third welfare component is from the change in fuel economy itself and equals the actual (not perceived) lifetime fuel-saving benefits per unit reduction in *g*, less the incremental increase in the vehicle cost, times the number of vehicles. If consumers are far sighted, the net effect is a welfare loss since from (6), $C_{\hat{g}-\bar{g}} > m(p_G + t_G)$—that is, the marginal cost from reducing fuel per 100 miles always exceeds the actual fuel-saving benefits, where the latter are correctly anticipated by consumers. However, if consumers are myopic and underestimate the actual benefits from higher fuel economy that they will experience over the period, then the third welfare component can be positive. This is because at the point when the standard becomes binding, the marginal cost of improving fuel economy equals the perceived fuel-saving benefit, which is *less* than the actual fuel-saving benefit they will experience.

Functional Forms. We assume constant-elasticity demand functions for mileage and vehicles:

$$(8) \qquad m = \hat{m}\left(\frac{g}{\hat{g}}\right)^{\eta_m}, \;\; v = \hat{v}\left(1 - \frac{C + \Gamma - \hat{\Gamma}}{\hat{p}_v}\right)^{\eta_v}.$$

$\eta_m < 0$ is the elasticity of miles driven per vehicle with respect to fuel costs and $\eta_v < 0$ is the elasticity of vehicle demand with respect to changes in the vehicle price, accounting for changes in perceived lifetime fuel costs. Based on NRC 2002, Ch. 4, we assume the marginal cost of reducing g is linear (see also Rubin et al. 2006):

$$(9) \qquad C_{\hat{g}-\bar{g}}(\hat{q}) = \alpha + \beta(\hat{g} - \bar{g}) + \hat{q} - q^0,$$

where α and β are positive parameters. q^0 denotes other vehicle attributes in a preceding period; as a result, to the extent that emerging technologies are used to enhance other vehicle attributes in the current period, $\hat{q} > q^0$, and the marginal cost curve for improving fuel economy is shifted up (as in Austin and Dinan 2005). Finally, we assume E_G/λ, E_M/λ and μ are constant over the relevant range.[5]

Given a set of parameters and baseline values for variables, the single-vehicle model is easy to solve in a spreadsheet by incrementally reducing g, computing the incremental change in m and v from (8), and hence the incremental change in M and G from (7b) and marginal welfare effects from (7a). Integrating over a range of increments gives the welfare effect of a non-marginal policy change.

2.2. Multi-Vehicle Model

In this disaggregated model, the representative agent drives $i = 1 \ldots N^C$ cars and $i = N^C+1 \ldots N^T$ light trucks (again, vehicle choice is continuous on an economywide, per capita basis). Firms are homogeneous, and each now produces all of the vehicle types; prices, fuel consumption rates, external costs per mile driven, and the marginal cost of reducing fuel consumption differ across vehicles.

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[5] This seems reasonable given that proportionate changes in total oil consumption and vehicle miles traveled are modest in our policy simulations. Moreover, aggregate fatality risks from local pollution are roughly proportional to atmospheric concentrations (Burtraw et al. 1998).

Vehicle demands are given by the more general relation:

$$(10) \qquad v_i = \hat{v}_i \prod_{j=1}^{N^T} \left\{ 1 + \frac{C_j + \Gamma_j - \hat{\Gamma}_j}{\hat{p}_j} \right\}^{\eta_{ij}}, \; i, j = 1 \ldots N^T,$$

where η_{ii} is an own-vehicle price elasticity and η_{ij} $(j \neq i)$ is the elasticity of demand for vehicle *i* with respect to the price of vehicle *j*.

CAFE sets separate standards for the harmonic average miles per gallon across car and light-truck fleets, which, for our purposes, is equivalent to imposing maximum fuel-per-mile requirements, expressed as $\bar{g}^C$ for cars and $\bar{g}^T$ for trucks. When standards are binding:

$$(11) \qquad \sum_{i=1}^{N^C} (\bar{g}^C - g_i) v_i = 0, \qquad \sum_{i=N^C+1}^{N^T} (\bar{g}^T - g_i) v_i = 0.$$

Manufacturers choose fuel per 100 miles for each vehicle, and the sales mix, to maximize profits is $\sum_{i=1}^{N^T} \{ p_i - \hat{p}_i - C_i(\hat{g}_i - \bar{g}_i, \hat{q}_i \} v_i$ subject to (11), taking prices as given. This yields

$$(12a) \qquad \partial C_i(\hat{q}_i)/\partial g_i = \partial C_i(\hat{q}_j)/\partial g_j, \text{ for } i \neq j \text{ and either } i, j = 1 \ldots N^C \text{ or } i, j = N^C+1 \ldots N^T$$

$$(12b) \qquad p_i - \hat{p}_i - C_i = \delta_k (g^i - \bar{g}^k), \text{ for } i = 1 \ldots N^C \text{ and } k = C \text{ or } i = N^C+1 \ldots N^T \text{ and } k = T.$$

δ_C and δ_T are the shadow prices on the constraints for cars and trucks respectively.

(12a) states that within the car or light-truck class, the marginal cost of reducing fuel per 100 miles is equated across vehicles, while (12b) states that, within a vehicle class, sales prices increase by more or less than the increase in vehicle-production costs, according to whether fuel per mile is above or below the average for that class; that is, besides technology adoption, manufacturers also meet the fuel economy standard by tilting their sales mix toward fuel-efficient vehicles. If fuel economy credits could be traded across cars and light trucks this would effectively replace the separate standards with a single standard and would improve efficiency by equating the marginal cost of reducing fuel consumption across all cars and light trucks.

The welfare change from an incremental reduction in the maximum allowable fuel consumption rate $\bar{g}_k$ is the same as in the single-vehicle model, although we are now aggregating over vehicle types. The analogous expression to (7a) is:

$$(13) \qquad \overbrace{\left(\mu t_G - \frac{E_G}{\lambda} \right) \left(-\frac{dG}{d\bar{g}_k} \right)}^{\textit{gasoline reduction}} - \overbrace{\sum_{i=1}^{N^T} \frac{E_{Mi}}{\lambda} \left(-\frac{dM_i}{d\bar{g}_k} \right)}^{\textit{mileage increase}} + \overbrace{\sum_{i=1}^{N^T} \left\{ m_i (p_G + t_G) - \frac{\partial C_i(\hat{q}_i)}{\partial g_i} \right\} \frac{dg_i}{d\bar{g}_k} v_i}^{\textit{fuel economy}}.$$

The multi vehicle model is solved in a spreadsheet that selects values for the shadow prices, uses these to compute fuel per 100 miles, vehicle prices, and vehicle demands from (10) and (12), and iterates over the shadow prices until constraints in (11) are met. We incrementally tighten the fuel-per-100-miles standard to a given level for one vehicle class, obtaining welfare effects by integrating over (13), and then repeat this procedure for the other vehicle class.

3. PARAMETER VALUES

Here we discuss benchmark parameter values, which are mostly representative of year 2000; alternative values are considered later.

3.1. Basic Vehicle Data

We first describe existing vehicle data for year 2000 and later adjust fuel economy or other vehicle attributes to account for possible technology adoption in the baseline scenario without regulation. Following NRC (2002) we distinguish four cars (subcompact, compact, midsize, and large) and six light-trucks (small SUV, mid SUV, large SUV, small pickup, large pickup, and minivan); relevant data for these vehicle classifications are summarized in Table 1.

Certified fuel economy for 2000 is 27.4, 20.6 and 24.0 mpg across cars, light trucks, and all vehicles, respectively, or 3.65, 4.85 and 4.17 gallons per 100 miles; we assume on-road fuel economy is 85 percent of the certified level (NRC 2002, Ch. 4). Following NRC (2002) we assume all vehicles are initially driven 15,600 miles in the first year, decreasing thereafter at 4.5 percent per year, over the 14-year life cycle. Actual lifetime fuel costs for vehicle i are therefore $15{,}600 \cdot \Sigma_{j=1}^{14}(p_G + t_G)g_i/(1+r^S+.045)^{j-1}$; r^S is the social discount rate, which, following practice at the Office of Management and Budget, is assumed to be 0.05, and $p_G + t_G$ is the retail fuel price, taken to be \$1.80 per gallon (higher fuel prices are considered later). Lifetime fuel costs vary from \$9,070 (subcompact) to \$16,500 (large SUV).

We calibrate parameters α_i and β_i of the marginal cost function for reducing g_i to cost data compiled by NRC (2002).[6] Marginal costs rise more rapidly for vehicles with lower initial fuel consumption rates, as indicated by their having higher β_is (Table 1); in fact, the marginal cost for cars as a group has a slope about twice that for light trucks as a group. In addition, the lifetime savings per gallon reduction in fuel per 100 miles is \$2,329; this greatly exceeds all the α_is, which reflect the initial cost of

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[6] We order technology options for each vehicle class analyzed in NRC (2002) by the ratio of average cost to the average percentage improvement in fuel economy; fitting regressions of the form in (9) to this data yields our coefficient estimates. The NRC cost estimates are expressed as retail price equivalents with a 40 percent markup assumed for parts supplier, automaker, and dealer. In this regard, they may overstate pure economic costs since some of the markup may reflect a transfer payment.

reducing fuel per 100 miles by a gallon assuming that, in the baseline, new technologies are not used to enhance other attributes.

3.2. Perceived Fuel Economy Benefits and Technology Adoption to Enhance Other Attributes

The ratio of perceived to actual lifetime fuel costs is given by:

$$\rho = \frac{\Sigma_{j=1}^{Y} 1/(1+r^{P}+.045)^{j-1}}{\Sigma_{j=1}^{14} 1/(1+r^{S}+.045)^{j-1}},$$

where $Y \leq 14$ is the horizon over which households consider fuel savings, and r^P is the private discount rate. We consider two scenarios for myopic consumers based on expert judgment in NRC (2002), Tables 4.2 and 4.3: a "high discount rate" scenario with $Y = 14$ and $r^P = 0.12$, and a "short horizon" scenario with $Y = 3$ and $r^P = 0$.[7] These scenarios imply $\rho = 0.74$ and 0.35, respectively.

We consider two scenarios that span possibilities for the extent of new technology adoption to enhance other attributes that would occur with no regulation. In one "without-alternative-value" scenario, there is no such technology adoption, or $\hat{q}_i = q_0$; in this case, with no regulation, new technologies would be deployed to reduce fuel consumption rates until the last condition in (5d) is satisfied. In the other "with-alternative-value" scenario, all new technology adoption in the absence of regulation enhances other attributes, with no change in fuel economy; in this case, $\hat{q}_i$ increases above q_0 until condition (5d) is satisfied. An intermediate case seems most plausible; the without-alternative-value scenario is hard to square with intense opposition to fuel economy regulation from the auto industry, while the other extreme assumes that consumers still prefer other enhancements to higher fuel economy, despite the run-up in fuel prices and the substantial increase in horsepower during the 1990s.

3.3. Vehicle Demand and Mileage Elasticities

We simulate an internal General Motors (GM) model of new vehicle sales to obtain a 10×10 matrix of own- and cross-price vehicle elasticities.[8] However, the own-price demand responses are too large as they include not only substitution between vehicles and reduced overall vehicle demand, but also

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[7] The first case is based on empirical studies finding that (implicit) private discount rates exceed market rates for a wide spectrum of energy saving products. However, very few studies apply to automobiles; one exception is Dreyfus and Viscusi (1995), who estimate implicit discount rates of 11–17 percent, although the average new-car-loan interest rate was 12.6 percent in their sample, suggesting that car buyers may have been liquidity constrained rather than myopic. The second case above is based on the views of some auto industry experts and is the assumption built into the U.S. Energy Information Administration's National Energy Modeling System.

[8] The GM model estimates demand responses for individual models with respect to the prices of a wide range of other models; we aggregate these response to be consistent with our vehicle classes.

substitution into used vehicles due to the temporary increase in the ratio of new to used vehicle prices; the last effect disappears in the long run as the fleet turns over. We therefore scale back the own-price elasticities to account for this (see Appendix B). The resulting 10×10 elasticity matrix is shown in Table 2: own-price elasticities vary between –1.40 and –3.20. For the single-vehicle model, where there are no cross-price effects, we assume η_v = –0.36 (see Appendix B for a justification). And we choose η_m = –0.125; accounting for the reduction in vehicle demand, this implies a rebound effect of around 6–10 percent across different scenarios.[9]

3.4. Local Pollution Costs

Tailpipe Emissions and Fuel Economy. In the single-vehicle model, we assume that local tailpipe emissions are proportional to mileage and independent of fuel economy, while in the multi-vehicle model we assume local emissions per mile are the same within both car and light-tuck classes. We validate these assumptions as follows (if they do not hold exactly, the welfare change from the gasoline reduction would be slightly increased).

Even though new cars and light trucks must satisfy the emissions per-mile-standard set up for their class, emissions rates may increase at a faster rate with vintage for vehicles with higher fuel consumption rates, if abatement technologies deteriorate significantly over time. In fact, Harrington (1997) identified the higher lifetime emission rates for high fuel consumption vehicles by mapping remote-sensing data on emissions by vehicle type and vintage in 1990 from the Arizona Inspection and Maintenance (I&M) Program to U.S. Environmental Protection Agency (EPA)–certified fuel economy data. However, these results need to be revisited because of increased durability of emissions control equipment and the rapid decline in new vehicle emissions rates since 1990.

We repeated Harrington's analysis using data on emission rates of volatile organic compounds (VOC), nitrogen oxides (NO_x), and carbon monoxide (CO) from the Arizona I&M program collected in 1995 and 2002.[10] The 1995 dataset showed that lifetime emissions rates were still significantly affected by fuel economy (although less so than in 1990); however, we were unable to find much of an effect in the 2002 dataset. As shown in Figure 2, projected CO, hydrocarbons, and NO_x emissions per mile for cars with certified fuel economy of 20 and 30 mpg are virtually indistinguishable over vehicle lifetimes; the same applies within trucks (see Fischer et al. 2005 for more details).

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[9] Our value for η_m is approximately consistent with evidence in Small and Van Dender (2006) and was confirmed in a personal communication with Ken Small on 1/8/2007.

[10] Sample sizes were 60,000 vehicles per month over a 12-month period for 1995 and 35,000 per month for 2002 (the difference being due to new exemption rules for new vehicles).

Local Tailpipe Emissions Damages. We obtained average emissions per mile over car and truck lifetimes using data in Figure 3, and above assumptions about miles driven in each year of the vehicle life. We multiply average emissions by (adjusted) damage estimates from Small and Kazimi (1995), Table 5, of 0.19 cents per gram for VOC, 0.69 cents per gram for NO_X, and zero for CO, and aggregate over pollutants.[11] This gives external damages of 1.1, 2.0, and 1.5 cents per mile for cars, light trucks, and all vehicles, respectively.

Upstream Emissions Leakage. The most important pollutant emitted during petroleum production, refining, transport, and storage is VOCs. In 1999, petroleum industry VOC emissions were 9.8 grams per gallon;[12] multiplying by 0.19 gives damages of 1.9 cents per gallon.

3.5. Global Pollution Costs

Nordhaus and Boyer (2000) provide a comprehensive assessment of the potential world damages from future global warming due to impacts on agriculture, coastal activities, human health, etc.; they also include a crude attempt to incorporate the risk of extreme climate change scenarios. This study, and other literature reviews by Pearce (2005) and Tol (2005), put the damage from today’s carbon emissions at around $10 to $50 per ton, though damages rise over time. In the *Stern Review* (Stern 2006), the marginal damage from carbon is put at a dramatically larger $311 per ton, although much of the difference is from their assumption that the discount rate on future utility is approximately zero, which is problematic in other contexts (Nordhaus 2007). For our benchmark, we follow NRC (2002) and assume a damage of $50 per ton, which is equivalent to 12 cents per gallon. (A gallon of gasoline contains 0.0024 tons of carbon.)

3.6. Congestion Costs

To our knowledge there has been only one previous attempt to estimate nationwide marginal congestion costs (MCCs): FHWA (1997) obtained an estimate of around 5 cents per mile, using speed-flow curves to estimate MCCs for selected urban and rural road classes and weighting these by respective mileage shares.

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[11] Damages are dominated by mortality effects, and we scale estimates to be consistent with the value of life for traffic fatalities assumed below. Although Small and Kazimi’s estimates apply to Los Angeles, where climate and topography is especially favorable to pollution formation, they are roughly consistent with estimates for other urban areas (e.g., McCubbin and Delucchi 1999).

[12] Calculated from EIA (2002) and EPA (1999), Appendix A-5.

We obtain an alternative estimate, by extrapolating results from a computational model of the metropolitan Washington, DC, road network (see Fischer et al. 2005 for model details and calibration). Fuel economy is a parameter in the model that affects driving costs; incrementally increasing this parameter, computing the welfare losses to households from extra congestion and dividing by the (aggregate) increase in mileage yields an estimate of MCC = 7.7 cents, averaged across all road classes and time of day for Washington, DC. Next, we obtain a relation between MCC and the mileage/pavement ratio from the Washington, DC, model by scaling up and down all baseline travel demands, holding road capacity fixed. We then inferred values for the mileage/pavement ratio, and hence MCC, for the 75 largest U.S. cities, using data on travel demand and road capacity in Schrank and Lomax (2002). Aggregating over cities using population shares (and assuming MCC = 0 for rural areas) yields a nationwide average MCC of 6.5 cents per mile. Based on the two estimates, we assume a nationwide MCC of 6.0 cents per mile.[13]

3.7. External Accident Costs

We follow a similar methodology to that in Miller et al. (1998) and Parry (2004) to estimate external accident costs per mile by vehicle type (see Appendix B for more detail and justification). This involves (a) using crash data to attribute fatal and various non-fatal injuries to vehicles in the accident; (b) valuing, for different injuries, quality of life costs, third-party medical burdens and property damages, productivity losses, and travel delay costs; and (c) converting costs for different vehicles to a per-mile basis. However, sorting out external from internal costs is difficult. Injury risks in single-vehicle crashes are usually viewed as internal, while pedestrian injuries are external. Whether injuries to others in multi-vehicle crashes are external is unclear: all else the same, one extra vehicle on the road raises the risk that other vehicles will collide, but if people drive more carefully in heavier traffic, a given accident will be less severe. We assume 50 percent of other vehicle injuries are external. Overall, we estimate the mean external cost is 4.39 cents per mile (Table 3).

Table 3, second row from the bottom, also shows that external costs are moderately higher than average for pickups and sub-compacts, but below average for minivans, mid-size cars, and small SUVs; as a result, vehicle weight/size and external costs have little correlation. However, our approach does not control for non-vehicle characteristics such as region, driver age, speed, prior crash record, alcohol use, gender, road class, weather, seatbelt use, etc.; for example, above-average external costs for small cars

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[13] This figure is an underestimate as it excludes non-recurrent congestion from road works and bad weather; congestion from accidents is incorporated below. We assume congestion costs per mile are the same for all vehicles as differences in vehicle length are small relative to average on-road distance between vehicles (FHWA 1997, Table V-23).

might be explained by their ownership concentration among young, inexperienced drivers, with greater propensity to drink. An econometric analysis by White (2004) that controls for a broad range of non-vehicle characteristics, estimates that the probability of a vehicle occupant being killed in a two-vehicle crash is 61 percent higher if the other vehicle is a light truck than if it is a car; for a pedestrian the risk is 125 percent higher if hit by a light truck. We develop an alternative estimate of external costs that accounts for this finding in a crude way, by assuming external costs are 80 percent greater for all light trucks than for all cars, keeping the mean accident cost across all vehicles constant at 4.39 cents per mile (see the last row of Table 3).[14]

3.8. External Costs of Oil Dependence

Economic analyses of the external costs of oil dependence have focused on two components. First is the "optimum tariff" due to U.S. monopsony power in the world oil market, which depends on how the Organization of Petroleum Exporting Countries (OPEC) and other oil producers might respond to a change in U.S. imports. Second is the expected cost of macroeconomic disruptions from price shocks that the private sector may not fully internalize, such as temporarily idled capital and labor; these costs have been assessed using postulated probability distributions for price shocks, estimated oil price-GDP elasticities, and assumptions about how firms and consumers internalize price risks. Estimates for the two components combined vary between around $0 and $14 per barrel, or 0 to 33 cents per gallon (e.g., CEC 2003, Table 3.12.; Leiby et al. 1997), NRC (2002) assumed a value of 12 cents per gallon. We use a benchmark value of 16 cents to make some allowance for higher oil prices.[15]

We choose this figure, as it can be justified based on other, careful analysis; nonetheless, it excludes potentially important geopolitical costs from oil dependence that are especially difficult to quantify. For example, buoyant oil revenues may help to fund terrorist groups and insurgents in Iraq and may embolden Iran to pursue nuclear-weapons capability or Russia to crackdown on political freedoms. Unilateral oil-conservation measures in the United States will have little near-term effect on these revenue flows through lowering the world oil price; however, ultimately the price effect could be greater if technologies developed at home are adopted in China and other large oil-consuming nations. There are

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[14] Our concern with CAFE's impact on external accident costs differs from that in the mainstream CAFE/safety literature, which instead examines implications for total fatality rates, with mixed findings (e.g., Crandall and Graham 1989; Kahane 1997; Khazzoom 1997; van Auken and Zellner 2002; Noland 2004). External costs are quite different, as they exclude own-driver fatality risk, and include traffic holdups, and a portion of non-fatal injuries to other road users, property damage, medical costs, productivity losses, etc.

[15] Whether the monopsony tariff component, which accounts for roughly half of this figure, should be included is questionable; it only applies if welfare is viewed from a domestic perspective, which conflicts with our measurement of carbon damages from a global perspective.

also substantial human and budgetary costs associated with the U.S. military presence in the Middle East. Nonetheless, according to Delucchi and Murphy (2004), these costs amount to a modest 6 cents per gallon or less; moreover, many analysts assume that troop deployments would not be affected by a modest reduction in U.S. oil imports.[16]

3.9. Government Parameters

The gasoline tax is 40 cents per gallon.[17] In a dynamic setting, the social value per dollar of highway investment spending would be $(1+r^H)/(1+r^S)$, where r^H is the rate of return on highway spending: Evidence on this is mixed, although a plausible range might be r^H = 0–0.3 (e.g., Shirley and Winston 2004; TRB 2006). Using this range and r^S = 0.05 gives u_X / λ = 0.95 –1.24; we consider this range later, but for the benchmark case we assume $\mu = 1$.

4. RESULTS

4.1. Single-Vehicle Model

Benchmark Results. Table 4 shows results from the single-vehicle model for a 4-mpg increase in fuel economy above currently observed levels. All variables represent present discounted values over a 14-year horizon, expressed on an annualized basis. Welfare effects vary from a gain of \$3.2–6.5 billion in the short-horizon scenario to either no change or a loss of \$8.4 billion, in the far-sighted/with-alternative-value scenario.

Without alternative value, and far-sighted or high-discount-rate consumers, the fuel economy standard is non-binding, because in the absence of regulation, emerging technologies would be adopted to raise fuel economy by more than 4 mpg. In the other four cases, regulation is binding and gasoline consumption falls by about 13 percent in three of them, and by 4.7 percent in the short-horizon/without-alternative-value scenario. In all four of these cases, there is an efficiency loss of \$0.4–1.2 billion from

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[16] A further dimension to the oil-dependence problem is that the market is subject to manipulation by a few countries with extensive, and nationalized, oil reserves. Although the global efficiency costs of OPEC price manipulation may be large (Greene and Ahmad 2005), this does not in and of itself drive any wedge between the domestic demand for oil and the oil-import supply curve in the United States. If the United States were a price taker, there would be no domestic efficiency rationale for reducing oil demand on these grounds, while to the extent that the United States has market power and can influence OPEC behavior and the world price, this is taken into account in computations of the optimal tariff from a domestic welfare perspective. If welfare was instead viewed on a global basis, the gains to other oil consuming countries from U.S. ability to counteract OPEC price manipulation would need to be included.

[17] 18 cents at the federal level and, on average, 22 cents at the state level (from dividing state tax receipts by gasoline sales using DOC 2000, Tables 1022 and 1174).

the reduction in gasoline, as the combined external costs from oil dependence, carbon emissions, and local upstream emissions (30 cents per gallon) fall short of the fuel tax (40 cents per gallon). There is a further efficiency loss of $1.4–2.8 billion from the increase in mileage; although the rebound effect is only 6–10 percent (accounting for reduced vehicle demand), the efficiency loss is still significant because mileage-related externalities are relatively large (12 cents per mile, equivalent to $2.45 per gallon at initial, on-road fuel economy). In the short-horizon cases, welfare gains from the increase in fuel economy itself easily outweigh efficiency losses from the reduction in gasoline and increase in mileage. However, this does not apply in the high discount rate case, leaving an overall net welfare loss of $2.4 billion, while with far-sighted consumers, the increase in fuel economy results in a welfare loss, not gain, of $4.7 billion.[18]

Sensitivity Analysis. Table 5 shows the sensitivity of welfare effects to different assumptions. We vary the stringency of the fuel economy standard, the retail fuel price, the mileage and vehicle demand elasticities, the social discount rate, the marginal value of government tax revenue, fuel-related externalities, and the cost of technology adoption. The main qualitative findings in the benchmark results are robust to nearly all these parameter variations. That is, when consumers are far sighted or have high discount rates, tightening fuel economy standards typically reduces efficiency in the with-alternative-value scenarios and has no effect in the without-alternative-value case, while tightening standards improves efficiency when consumers have short horizons.

In quantitative terms however, the results can be somewhat sensitive to different assumptions. For example, in the short-horizons cases, welfare gains are about twice as high if fuel prices are $2.50 per gallon rather than $1.80, while gains are cut in half if the social discount rate for fuel savings is 12 percent rather than 5 percent. When fuel-related externalities are raised to 80 cents per gallon—that is, carbon damages are $220 per ton, or oil-dependency costs are $28 per barrel—welfare gains are increased by 70 percent or more in the short-horizons cases, become positive in the high discount rate/with-alternative-value scenario, but remain slightly negative in the far-sighted/with-alternative-value scenario. And when standards are raised by 2 mpg rather than 4 mpg, welfare effects vary from a loss of $3.5 billion to a gain of $4.5 billion.

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[18] Austin and Dinan (2005) consider a scenario equivalent to our far-sighted/with-alternative-value scenario, ignoring impacts on externalities. They estimate that a 10 percent reduction in gasoline consumption would induce welfare losses of $3.6 billion, assuming a rebound effect of 20 percent; for the same rebound effect and fuel reduction, the corresponding welfare loss in our model would be $3.5 billion.

4.2. Multi-Vehicle Model

Table 6 displays results for the multi-vehicle model for a 4-mpg increase in both car and light-truck standards under benchmark parameter assumptions. The overall welfare effects are roughly similar to those predicted by the single-vehicle model (within 1−7 percent across the different scenarios).

The main reason for this similarity is that even though there is some substitution away from larger cars, SUVs, and pickup trucks toward smaller vehicles (as indicated by the larger percentage reduction in vehicle sales for the former), changes in vehicle fleet composition play a relatively minor role in meeting the fuel economy standard (Kleit 2004, Greene 1991). Instead, more than 90 percent of the improvement comes from technology adoption, as indicated by the substantial increase in fuel economy across all vehicles. This means that differences in (mileage-related) external costs across vehicles play a minor role in welfare effects; this applies even if we use the alternative method in Table 3 for measuring accident externalities across cars and light trucks.

In the lower portion of Table 6, we consider an increase in car and light-truck standards but allow trading of fuel economy credits across all vehicles, keeping the total reduction in gasoline use the same as in the corresponding scenario without trading by slightly adjusting regulatory stringency. In this case, slightly more of the burden of fuel economy improvement is borne by trucks and slightly less by cars, given that marginal compliance costs without trading are larger for cars than trucks, though only moderately so.[19] Consequently, the fuel economy component of the welfare change is moderately greater.[20]

Finally, in Table 7 we raise the light-truck standard by 6.8 mpg above the 2000 standard to equate it with the car standard of 27.5 mpg; the upper and lower halves of Table 7 illustrate cases with and without trading of credits across cars and trucks. (This time, we allow fuel consumption to vary between scenarios with and without trading.) Qualitative results are similar to those above; welfare gains are positive if consumers have short horizons, but zero or negative when consumers are far-sighted or have excessive discount rates. And allowing for trading of fuel economy credits reduces welfare losses/increases welfare gains, but the effect is not huge.[21]

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[19] Even though the marginal cost curve for cars has twice the slope of that for light trucks (compare the β parameters in Table 1), increasing truck fuel economy from 20.6 to 24.6 mpg requires a reduction of 0.79 gallons per 100 miles; increasing car fuel economy from 27.4 to 31.4 mpg requires a smaller reduction of 0.46 gallons per 100 miles.

[20] This finding is broadly consistent with Austin and Dinan (2005). However Rubin et al. (2006) estimate much larger cost savings; they also find that cost savings from credit trading within manufacturers easily exceed those from credit trading between (heterogeneous) firms.

[21] Welfare losses from the increase in mileage are smaller for this policy; this is because the offsetting reduction in the vehicle stock is greater when light-trucks bear a disproportionate burden of regulatory costs, as demand for light truck vehicles is more price-sensitive than for cars.

4.3. Should CAFE Standards Be Tightened?

What are we to make of the above results? For those who believe consumers have short horizons, tightening CAFE seems justifiable on efficiency grounds, although we ourselves are reluctant to side with this view, unless solid econometric evidence (rather than anecdotal evidence) emerges in its favor. On the other hand, for those who reject the fuel economy undervaluation hypothesis, whether tightening CAFE would have much effect, or produce large efficiency losses, is difficult to gauge ex ante; it depends on whether state-of-the-art technologies that can improve fuel economy might also have value in alternative-vehicle enhancements.

While we are eager for the federal government to phase in carbon and oil taxes that reflect marginal external costs,[22] in the meantime, if we had to make an immediate recommendation on CAFE, it would be to gradually raise the standards over time. We cannot justify this position on a compelling cost–benefit analysis, nor can we be entirely confident that the policy would have much impact above fuel economy improvements that might occur in the absence of regulation. Rather, this recommendation is based on our subjective view that more likely than not, additional benefits from higher fuel economy that have not been quantified in the mainstream externality literature (see below), outweigh the possible downside efficiency costs of a gradual tightening of the standards over time. As the reader may have guessed, we are sympathetic to certain arguments on either side of the CAFE debate, and it has been a struggle to form our own judgment on the issue.

5. CONCLUSION

In addition to the usual caveats about the need to update the results as evidence on parameter values improves over time, we finish up by discussing additional issues that are not handled in our analysis.

First, higher fuel economy standards may produce benefits that are difficult to quantify and that are excluded from the above analysis. For example, regulation may promote the development of fuel-saving technologies for which the social rate of return exceeds the return on other innovative activity that might be crowded out with enhanced R&D into vehicle fuel economy. Although this is an empirical question that needs attention in future research, we suspect that the social return on fuel-saving

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[22] Taxes have a number of advantages over quantity-based regulations like cap-and-trade carbon permits (Parry 2003; Nordhaus 2006). For example, energy tax revenue might be used to reduce other distortionary taxes, while freely allocated permit systems are inequitable as they transfer large rents from energy consumers to (wealthy) stockholders in energy companies. Volatility in permit prices can also deter large up-front investments in cleaner technologies. `

technologies might be quite large, given their potential for deployment in large, rapidly industrializing nations such as China. Thus, advances in technology driven by regulation at home may have a multiplier effect on addressing the threat of climate change and the geopolitical dimensions of western dependence on oil from unstable regions. Another possible benefit is that if the United States were to implement fuel economy regulation and other serious measures to limit greenhouse gas emissions, this might shift international pressure on climate control away from the United States towards developing nations.

A second caveat is that we do not model the potential for CAFE to affect vehicle weight or size. Allowing manufacturers to improve fuel economy by downweighting, in addition to changing the vehicle sales mix, would lower the costs of regulatory compliance. The impact on external accident costs is unclear and would depend in part on how the weight discrepancy between cars and light trucks is affected.

Finally, we assume the fuel tax is exogenous. In practice, as fuel economy improves and the base of gasoline taxes is eroded, this will increase pressure at both the state and federal level for an increase in fuel tax rates, which would be welfare improving (Parry and Small 2005); by ignoring this possible policy interdependence, our analysis may understate the ultimate welfare effects of CAFE.

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APPENDIX A: ANALYTICAL DERIVATIONS

Deriving Equation (7)

Using (1)–(3), the household budget constraint, and assuming binding regulation $g = \bar{g}$, the representative agent’s indirect utility function, *V*(.), with fuel costs correctly valued, is defined by:

$$\text{(A1)} \quad V(\bar{g}, E(\bar{M}, \bar{G}), F, H) = MAX\ u(D(v, m, \bar{H}, q), X) - E(\bar{M}, \bar{G}) + \lambda\left\{I + F - p_X X - [\hat{p}_v + C(\hat{g} - \bar{g}, \hat{q}) + (p_G + t_G) m\bar{g}]v\right\}.$$

Partially differentiating (A1) gives:

(A2) $V_{\bar{g}} = -\lambda[(p_G + t_G)m - C_{\hat{g}-\bar{g}}(\hat{q})]v, \quad V_{\overline{M}} = -E_{\overline{M}}, \quad V_{\overline{G}} = -E_{\overline{G}}, \quad V_F = \lambda, \quad V_H = u_H$.

Totally differentiating the indirect utility function in (A1) with respect to $\bar{g}$ gives:

(A3) $$\frac{dV}{d\bar{g}} = V_{\bar{g}} + V_{\overline{M}}\frac{dM}{d\bar{g}} + V_{\overline{G}}\frac{dG}{d\bar{g}} + V_F\frac{dF}{d\bar{g}} + V_H\frac{dH}{d\bar{g}}.$$

Substituting (A2) in (A3) and multiplying by –1 gives:

(A4) $$-\frac{1}{\lambda}\frac{dV}{d\bar{g}} = [(p_G + t_G)m - C_{\hat{g}-\bar{g}}(\hat{q})]v - \frac{E_{\overline{M}}}{\lambda}\left(-\frac{dM}{d\bar{g}}\right) - \frac{E_{\overline{G}}}{\lambda}\left(-\frac{dG}{d\bar{g}}\right) - \frac{dF}{d\bar{g}} - \frac{u_H}{\lambda}\frac{dH}{d\bar{g}}.$$

Multiplying and dividing the last two terms in (A4) by $t_G dG/d\bar{g}$ and substituting for μ as defined in (7b), we obtain (7a).

The first two expressions in (7b) are obtained from differentiating $M = vm$ and $G = gM$ with respect to $\bar{g}$.

APPENDIX B: SOME DETAILS ON MODEL CALIBRATION

Adjusting own-price vehicle elasticities from the GM model

We simulate a dynamic model of vehicle choice, developed by Harrington et al. (2003), to obtain long-run estimates of the own-price elasticities for cars as a group, denoted $\hat{\eta}_{CC}$, and light trucks as a group, denoted $\hat{\eta}_{TT}$. Results are $\hat{\eta}_{CC}$ = –0.79 and $\hat{\eta}_{TT}$ = –0.85. We then express the own price elasticity for car *i* computed from the GM model as $\eta_{ii} = \sum_{j\neq i}\eta_{ji}v_j/v_i + (\eta_{ii} - \sum_{j\neq i}\eta_{ji}v_j/v_i)$, where *i*, *j* = 1…$N^C$. The first component in this expression captures the substitution effects among cars. The second component encompasses all other effects—reduced overall vehicle demand, substitution into trucks, *and* people holding onto vehicle *i* longer; to remove the last effect, we multiply the second component by $\hat{\eta}_{CC}/\tilde{\eta}_{CC}$, where $\tilde{\eta}_{CC}$ is the own-price elasticity for cars as a group from the GM model, equal to –2.25. Light-truck elasticities are similarly scaled using $\hat{\eta}_{TT}/\tilde{\eta}_{TT}$, where $\tilde{\eta}_{TT}$ = –0.97.

Own-price vehicle elasticity in the single-vehicle model

From simulating the Harrington et al. (2003) model for a 1 percent increase in the price of all cars and light trucks, we choose η_v = –0.36 for the single-vehicle model. In the GM model the aggregate vehicle demand elasticity is approximately –1.0, which is consistent with other estimates (e.g., McCarthy 1996, page 543). However, these other estimates are too elastic for our purposes as they are short rather than long run and include substitution between new and used vehicles.

Estimating external accident costs

Crash data averaged over 1998–2000 is used to assign traffic injuries to different vehicle types.[23] For single-vehicle crashes we assume occupant injury risks are internal, while injuries to pedestrians and cyclists are external. In crashes involving $n > 1$ vehicles, each vehicle is responsible for $1/n$ of the pedestrian/cyclist injuries, which are external, and $1/(n-1)$ of the injuries to other vehicle occupants.

Traffic delay, property damage, medical costs, emergency services, and administrative costs are divided equally among vehicles in the crash. We assume 100 percent of travel delay costs, 75 percent of property damages, and 85 percent of other costs (which are mainly covered by group insurance) are external.[24] Productivity losses at work and home to pedestrians and 50 percent of others injured in multi-vehicle crashes are external; for single-vehicle crashes, only the tax revenue components (assumed to be 40 percent) of workplace productivity losses is taken as external. We use estimates from NHTSA (2002b), Table A-1, to value quality of life costs, property damage, travel delay, productivity, medical, and administrative costs for different injury categories. Aggregate external costs per vehicle were converted to per mile costs using estimates of annual miles driven across vehicle types.[25]

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[23] We use the FARS (Fatality Analysis Reporting System) data for all accidents involving a fatality and the GES (General Estimates System) data for all other accidents (both are collected by the National Highway Traffic Safety Administration). The GES data provides an extrapolation of national estimates based on a representative sample of police-reported crashes; following Miller et al. (1998), page 18, we scale up non-fatal injuries by 12 percent and 9 percent for police and survivor under-reporting, respectively. Both the FARS and GES provide information on the vehicles involved in each accident and driver characteristics. Injuries are classified according to the system in police reported data: fatality (K), disabling (A), evident (B), possible (C), property damage only (O), injured severity unknown (UI), unknown if injured (U).

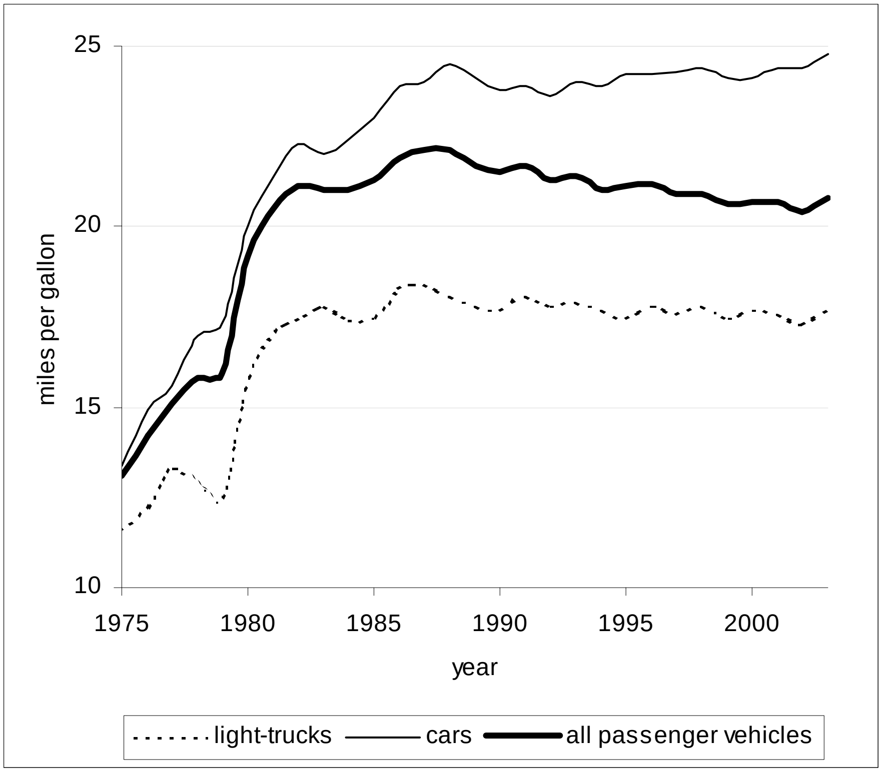
[24] If insurance is truly lump sum and premiums do not change in response to accidents, then all property damage is external. In practice people pay deductibles, and premiums vary, albeit very weakly, with stated annual mileage. Moreover, individuals typically pay higher premiums for three years following a claim, though the value of these extra payments is a minor fraction of the property damage (if not, there would be little incentive for insurance).

If a driver injures someone else, they may also be liable for damages though the tort system. However to be liable, the driver would have be judged at fault; yet much of the problem is that additional traffic on the road raises the risks of collisions, even if no one is driving recklessly. And even if an individual is judged to be liable, they may have very limited resources, certainly not the several million dollars needed to compensate for the value of life if someone else is killed.

[25] Mileage shares for vehicle classes were obtained from the National Personal Transportation Survey, weighting results from the 1995 and 2001 surveys by 1/3 and 2/3 respectively. Total mileage per vehicle class was obtained by multiplying these shares by economywide annual passenger vehicle mileage, averaged over 1998–2000, of 2,471 billion (from www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSFAnn/TSF2000.pdf).

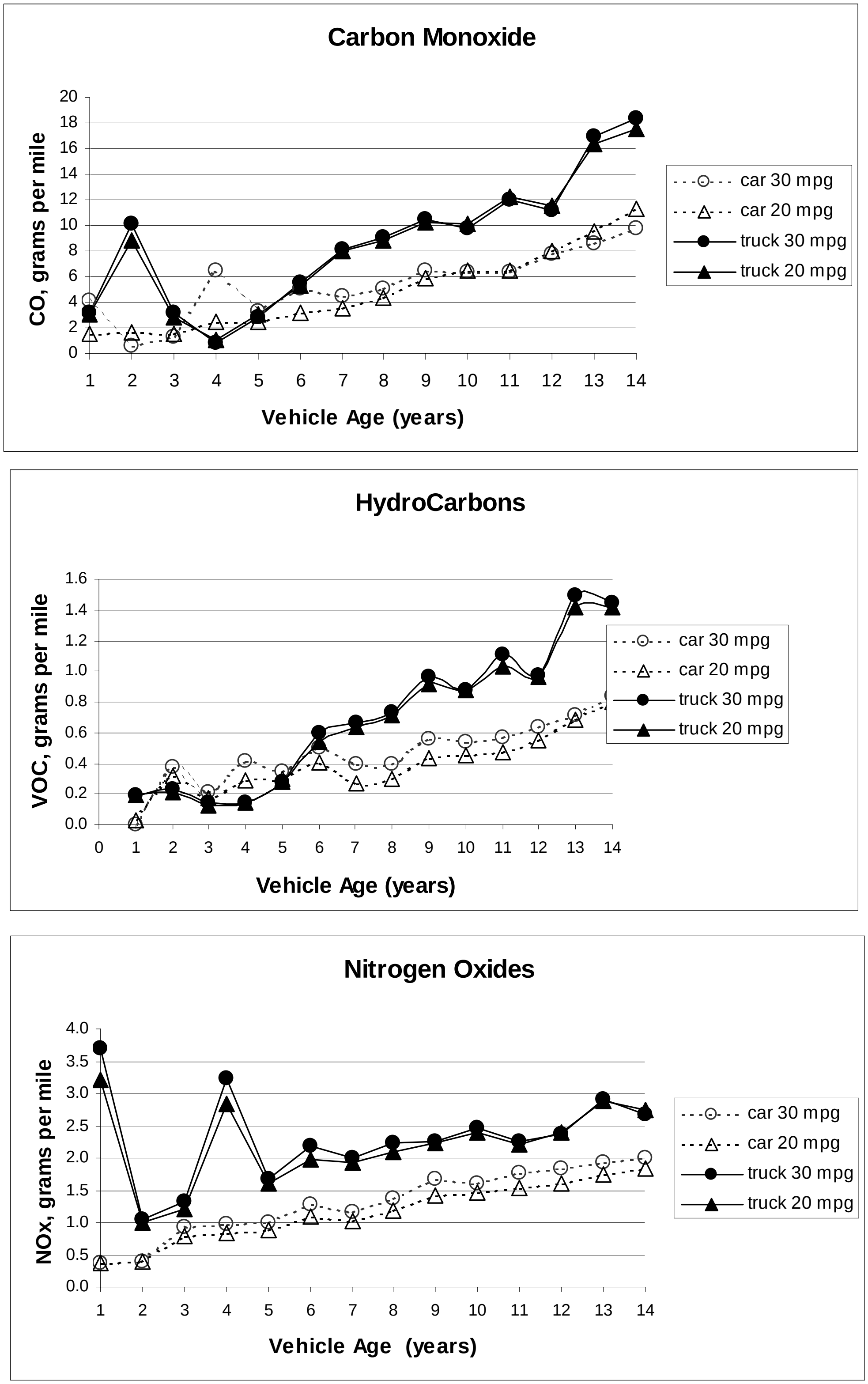
FIGURES AND TABLES

Figure 1. Fuel Economy Averages for Model Years 1978–2002



Source: NHTSA (2002a).

Figure 2. Fuel Economy and Emissions Deterioration Rates



Notes. Emissions rates are obtained by regressing emissions on fuel economy for vehicles of a given age, and reading off emissions from this relation at miles per gallon of 20 and 30.

Table 1. Year 2000 Vehicle Data

Vehicle class	Sales (thousands)	Initial price, $	Initial certified fuel economy		Actual lifetime fuel costs, $[a]	fuel economy cost parameters[b]	
			mpg	gal/100 miles		α^i	β^i
cars							
subcompact	756	15,280	30.2	3.3	9,070	368	2,892
compact	2,650	15,647	29.1	3.4	9,412	310	2,789
midsize	3,205	21,907	26.2	3.8	10,454	81	2,638
large	748	25,266	23.9	4.2	11,460	641	1,569
total cars	7,359	19,314	27.4	3.6	9,989	250	2,610
light trucks							
small SUV	617	18,571	23.3	4.3	11,755	336	1,559
mid SUV	1,672	27,557	20.3	4.9	13,493	85	1,390
large SUV	834	34,051	16.6	6.0	16,500	174	818
small pickup	1,026	17,551	22.2	4.5	12,338	102	1,705
large pickup	2,121	23,362	22.4	4.5	12,228	201	936
minivan	1,200	24,490	17.9	5.6	15,302	243	1,563
total trucks	7,470	24,481	20.6	4.9	13,292	176	1,282
total cars and trucks	14,829	21,917	24.0	4.2	11,418	213	1,941

Notes

[a] Fuel costs are discounted at 5 percent.

[b] α^i is the cost of incorporating technologies to reduce fuel consumption per 100 miles by one gallon below current levels, assuming emerging technologies are not used to enhance other vehicle attributes. β^i is the rate at which marginal costs increase.

Sources. Sales data is compiled from *Wards Automotive Handbook 2001*, while vehicle prices are a sales-weighted average of prices for individual models from *www.Edmunds.com*. To classify vehicles according to the NRC subgroups, we used a combination of the Wards descriptions and EPA classifications: luxury vehicles, two-seaters, large vans, and hybrids were excluded.

Table 2. Vehicle Demand Elasticites

	sub-compact	compact	mid size	large	small SUV	mid SUV	large SUV	small pickup	large pickup	minivan
subcompact	**-2.18**	1.17	0.35	0.00	0.02	0.02	0.00	0.07	0.00	0.01
compact	0.27	**-2.07**	0.58	0.01	0.02	0.02	0.00	0.03	0.01	0.02
mid Size	0.12	0.80	**-1.88**	0.36	0.03	0.10	0.00	0.03	0.02	0.06
large	0.02	0.12	1.98	**-2.24**	0.00	0.10	0.00	0.01	0.02	0.10
small SUV	0.04	0.32	0.11	0.00	**-3.20**	0.11	0.00	0.08	0.02	0.02
mid SUV	0.04	0.24	0.45	0.07	0.17	**-2.58**	0.24	0.13	0.23	0.27
large SUV	0.01	0.03	0.16	0.06	0.02	1.09	**-1.88**	0.02	0.39	0.43
small pickup	0.04	0.14	0.12	0.00	0.04	0.09	0.00	**-2.55**	0.38	0.03
large pickup	0.01	0.04	0.07	0.01	0.02	0.08	0.05	0.32	**-1.40**	0.03
minivan	0.03	0.07	0.16	0.07	0.01	0.14	0.04	0.01	0.04	**-2.41**

Sources. From simulating the GM model and adjusting the own-price elasticities (see Appendix B).

Table 3. External Accident Costs Across Vehicles
(cents per mile)

Cost component	cars				light trucks						
	sub-comp.	comp.	mid size	large	small SUV	mid SUV	large SUV	small pickup	large pickup	minivan	average
Quality of life costs											
pedestrains	1.20	0.85	0.61	0.90	0.54	0.72	0.37	0.87	0.88	0.53	**0.76**
other vehicle occupants	1.94	1.66	1.27	1.79	1.34	1.78	0.95	2.13	2.67	1.12	**1.65**
Property damage	0.51	0.39	0.26	0.30	0.20	0.26	0.13	0.31	0.24	0.20	**0.29**
Work/household prod. loss	0.67	0.52	0.38	0.49	0.31	0.47	0.21	0.49	0.47	0.29	**0.44**
Traffic holdups	0.29	0.22	0.15	0.17	0.11	0.15	0.07	0.17	0.14	0.12	**0.17**
Medical, emerg. serv., admin.	1.85	1.36	0.89	1.06	0.78	0.84	0.47	1.28	1.01	0.67	**1.07**
Total	**6.46**	**5.00**	**3.56**	**4.71**	**3.27**	**4.23**	**2.21**	**5.25**	**5.41**	**2.93**	4.39
Alternative method	**3.28**	**3.28**	**3.28**	**3.28**	**5.91**	**5.91**	**5.91**	**5.91**	**5.91**	**5.91**	4.39

Sources. See Appendix B for estimation methods and data sources. The alternative method re-allocates external costs across cars and light trucks as a group in proportion to fatality risks to other road users estimated in White (2004).

Table 4. Benchmark Results for Single-Vehicle Model

(effect of 4 mpg increase in fuel economy standard)

	Far-sighted consumer		Myopic consumers high discount rate		Myopic consumers short horizons	
alternative value	without	with	without	with	without	with
Certified fuel economy in free market baseline						
gallons per 100 miles	2.8	4.2	3.2	4.2	3.8	4.2
miles per gallon	35.3	24.0	31.0	24.0	26.4	24.0
Change in gasoline from free market baseline						
billion gallons (discounted)	0	-12.3	0	-12.2	-4.4	-12.1
%	0	-13.4	0	-13.3	-4.7	-13.2
Change in mileage, %	0	1.1	0	1.1	0.6	1.3
Change in vehicle sales, %	0	-0.9	0	-0.8	-0.1	-0.7
Rebound effect, %	0	6.4	0	6.9	10.3	7.6
Components of welfare change, $billion (discounted)						
total	0	-8.4	0	-2.4	3.2	6.5
gasoline reduction	0	-1.2	0	-1.2	-0.4	-1.2
mileage increase	0	-2.4	0	-2.6	-1.4	-2.8
fuel economy	0	-4.7	0	1.4	5.1	10.6
Welfare change per gallon of fuel reduction, $	0	-0.69	0	-0.20	0.74	0.54

Table 5. Sensitivity Analysis for the Single-Vehicle Model
(welfare effect, $billion)

	Far-sighted consumers		Myopic consumers high discount rate		Myopic consumers short horizons	
alternative value	without	with	without	with	without	with
Benchmark results	0	-8.4	0	-2.4	3.2	6.5
Increase in fuel economy standard (4 miles per gallon)						
2 miles per gallon	0	-3.5	0	-0.3	0	4.5
8 miles per gallon	0	-20.0	0	-9.6	6.4	6.0
Gasoline price ($1.80 per gallon)						
$1.50 per gallon	0	-8.5	0	-3.5	1.9	3.9
$2.50 per gallon	0	-8.0	0	0.3	6.4	12.7
Miles per vehicle elasticity (-0.125)						
-0.05	0	-6.4	0	-0.3	4.1	8.8
-0.25	0	-11.7	0	-5.9	1.8	2.8
Demand for vehicles elasticity (-0.36)						
0	0	-10.3	0	-4.1	3.0	5.1
-0.8	0	-6.1	0	-0.3	3.5	8.3
Social discount rate (0.05)						
0.12	0	-7.5	0	-3.2	1.4	3.2
Marginal value per $ of government spending ($1.00)						
$0.95	0	-8.1	0	-2.2	3.3	6.8
$1.25	0	-9.6	0	-3.6	2.8	5.3
Fuel-related external costs (30 cents per gallon)						
0	0	-12.0	0	-6.1	1.9	2.9
80 cents per gallon	0	-2.2	0	3.7	5.4	12.6
initial cost of a gallon reduction in fuel per 100 miles, α ($213)						
$107	0	-8.5	0	-2.5	2.7	6.6
$426	0	-8.5	0	-2.5	3.5	6.6

Notes. Figures in parentheses in the first column indicate benchmark parameter values.

Table 6. Results from the Multi-Vehicle Model
(effect of 4 mpg increase in fuel economy standard)

	Far-sighted consumers		Myopic consumers high discount rate		Myopic consumers short horizons	
alternative value	without	with	without	with	without	with
No trading of fuel economy credits						
Change in certified miles per gallon						
subcompact	0	4.2	0	4.2	2.2	4.2
compact	0	4.0	0	4.0	2.1	4.0
midsize	0	3.6	0	3.6	1.9	3.6
large	0	5.2	0	5.2	2.5	5.2
small SUV	0	3.9	0	3.9	1.9	3.9
mid SUV	0	3.6	0	3.6	1.8	3.6
large SUV	0	4.4	0	4.4	2.3	4.4
small pickup	0	3.4	0	3.5	1.7	3.5
large pickup	0	4.3	0	4.3	2.2	4.3
minivan	0	3.6	0	3.6	1.8	3.6
Change in vehicle sales, %						
subcompact	0	2.25	0	1.60	1.00	1.89
compact	0	0.14	0	0.15	0.54	0.15
midsize	0	-2.06	0	-1.54	-0.67	-1.77
large	0	-2.40	0	-1.87	-1.76	-2.12
small SUV	0	2.47	0	1.72	1.72	2.05
mid SUV	0	-0.12	0	-0.08	0.04	-0.10
large SUV	0	-2.66	0	-2.01	-1.05	-2.31
small pickup	0	2.34	0	1.65	1.36	1.95
large pickup	0	-3.98	0	-2.90	-1.18	-3.38
minivan	0	0.62	0	0.48	0.68	0.55
Change in gasoline, %	0	-13.7	0	-13.6	-6.2	-13.6
Components of welfare change, $billion (discounted)						
total	0	-8.6	0	-2.9	3.8	7.0
gasoline reduction	0	-1.3	0	-1.3	-0.6	-1.3
mileage increase	0	-2.6	0	-3.1	-1.8	-2.9
fuel economy	0	-4.7	0	1.6	6.2	11.2
Welfare change per gallon of fuel reduction, $	0	-0.65	0	-0.22	0.55	0.54
Trading of fuel economy credits						
Change in gasoline, %	0	-13.7	0	-13.6	-6.2	-13.6
Welfare change, $billion (discounted)						
total	0	-7.5	0	-2.7	4.4	7.6
fuel economy	0	-3.6	0	1.7	6.8	11.8
Welfare change per gallon of fuel reduction, $	0	-0.57	0	-0.21	0.64	0.58

Table 7. Raising Light-Truck Standard to Car Standard

	Far-sighted consumers		Myopic consumers high discount rate		Myopic consumers short horizons	
alternative value	without	with	without	with	without	with
No trading of fuel economy credits						
Change in gasoline, %	0	-14.3	0	-13.9	-4.5	-14.0
Components of welfare change, $billion (discounted)						
total	0	-7.4	0	-2.5	2.5	7.2
gasoline reduction	0	-1.4	0	-1.3	-0.4	-1.4
mileage increase	0	0.3	0	-0.9	-1.2	-0.4
fuel economy	0	-6.3	0	-0.3	4.1	9.0
Welfare change per gallon of fuel reduction, $	0	-0.54	0	-0.19	0.58	0.53
With trading of fuel economy credits						
Change in gasoline, %	0	-15.1	0	-14.8	-7.6	-14.9
Components of welfare change, $billion (discounted)						
total	0	-6.3	0	-1.4	3.9	8.1
gasoline reduction	0	-1.3	0	-1.3	-0.7	-1.3
mileage increase	0	-0.8	0	-1.8	-1.4	-1.4
fuel economy	0	-4.2	0	1.7	6.0	10.8
Welfare change per gallon of fuel reduction, $	0	-0.44	0	-0.10	0.54	0.57