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Should Corporate Average Fuel Economy (CAFE) Standards Be Tightened?

Ian W.H. Parry, Carolyn Fischer,
and Winston Harrington

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Abstract

This paper develops analytical models to estimate the welfare effects of higher Corporate Average Fuel Economy (CAFE) standards on new passenger vehicles. The analysis incorporates a broad range of fuel- and driving-related externalities, fuel taxes, different assumptions concerning consumers' valuation of fuel saving technologies and their alternative value in enhancing other vehicle attributes, and endogenous vehicle fleet composition. To implement the analysis, we develop estimates of CAFE's impact on local pollution, nationwide congestion, and traffic accidents. We find that higher fuel economy standards can produce anything from moderate welfare gains, to very little or no effect, to substantial welfare losses, depending on how consumers value fuel economy technologies and their opportunity costs.

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

JEL Classification Numbers: R48, Q48, H23

Contents

1. Introduction.....	1
2. Analytical Models.....	6
A. Assumptions in the Single-Vehicle Model	6
B. Solution to the Single-Vehicle Model.....	11
3. Benchmark Parameter Values.....	17
A. Basic Vehicle Data.....	17
B. Cost of Improving Fuel Economy	18
C. Vehicle Demand and Mileage Elasticities	19
D. Local Pollution Costs	20
E. Global Pollution Costs.....	22
F. Congestion Costs	22
G. External Accident Costs.....	23
H. External Costs from Oil Dependency	25
I. Government Parameters	26
4. Results	26
A. Single-Vehicle Model	26
B. Multi-Vehicle Model.....	28
5. Conclusion	29
References.....	31
Appendix A: Analytical Derivations	36
Tables and Figures.....	37

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1. Introduction

The Corporate Average Fuel Economy (CAFE) program requires automobile manufacturers to meet standards for the sales-weighted average fuel economy of their passenger vehicle fleets; current standards are 27.5 mpg (miles per gallon) for cars and 20.7 mpg for light-duty trucks (SUVs, minivans, and pickups).¹ Recent attempts to sharply increase the standards have been blocked in Congress, though the National Highway Traffic Safety Administration (NHTSA), which has authority to set light-truck standards, has finalized an increase in that standard to 22.2 mpg by Model Year 2007.

Proponents of tighter CAFE standards emphasize the benefits of reducing carbon emissions, particularly after the U.S. withdrawal from the 1997 Kyoto Protocol, and the economy's dependence on a volatile world oil market, made increasingly jittery by recent price increases. The standards may also address a market failure associated with consumers' undervaluation of fuel economy, though this is much disputed (compare Gerard and Lave 2003 and Kleit and Lutter 2004). Furthermore, there is concern that average fuel economy of the new passenger vehicle fleet has fallen significantly from its peak in 1987, due to the rising share

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¹ Manufacturers must pay a penalty of \$55 per vehicle for every 1 mpg that their fleet average falls below the relevant standard; vehicles weighing more than 8,500 pounds (such as the Hummer H2 and Ford Excursion) are exempt.

of light-duty trucks which now account for just over half of new passenger vehicle sales (see Figure 1).

Gasoline accounts for 43% of U.S. oil consumption and 20% of carbon emissions (EIA 2002, Tables 5.11 and 12.3). Broad oil and carbon taxes are therefore far more cost-effective policies than CAFE, as they exploit options for reducing oil use and carbon emissions throughout the economy, rather than placing the entire burden on (new) passenger vehicles. Nonetheless, energy taxes are not being debated by policy stakeholders while CAFE is;² understanding the social welfare effects of tightening CAFE would enlighten this debate.

This paper develops and implements an analytical framework for assessing the social welfare effects of tightening CAFE standards, a framework that takes into account a number of important factors.

First, the analysis integrates CAFE's impact on a broad range of motor vehicle externalities, including carbon emissions and oil dependency, which are proportional to fuel use, as well as congestion and accidents, which increase through the "rebound effect," that is, the incentive to drive more when fuel costs per mile fall. We also model CAFE's impact on local air pollution, which is potentially affected by vehicle use, fleet composition, fugitive emissions from the petroleum industry, and the effects of fuel economy on the emission profiles of aging vehicles.

Second, we incorporate preexisting fuel taxes that work to raise fuel prices and internalize fuel-related externalities, considering scenarios when revenues are earmarked for highways and when they form part of general government revenue.

Third, we consider scenarios meant to span the diverse range of opinions among experts about how consumers value fuel saving technologies, and the full economic costs of adopting them, allowing for possible opportunity costs from forgoing their use in enhancing other vehicle attributes such as power, comfort, safety, and payload.

Fourth, we consider implications of changes in vehicle fleet composition when the net costs of improving fuel economy, and external costs, differ across vehicle types.

² For example, a recent high-profile report from a bipartisan commission recommended higher fuel economy standards (NCEP 2004).

We begin with a single vehicle model, where welfare effects of fuel economy standards are explicitly decomposed into terms with clear economic interpretation. The model is then extended to distinguish ten vehicle classes. This extension allows us to consider differential standards for cars and light trucks, induced changes in the vehicle sales mix, and cost savings from trading of fuel economy credits across cars and light-trucks.

We develop new estimates of parameters required to implement the model where prior empirical literature is patchy. Emissions inspection data is used to quantify lifetime vehicle emission rates and to assess the emissions/fuel economy relation. Results from a computational transport network model are extrapolated to estimate marginal congestion costs for the nation as a whole. Crash data is used to estimate external accident costs for the ten vehicle classes. Also, we account for some previously unexamined subtleties in measuring fuel economy in absence of regulation, vehicle demand elasticities, and the rebound effect.

In previous literature, the usual approach has been to measure welfare effects of fuel economy regulations by estimating lifetime fuel saving benefits minus added vehicle costs (e.g., Yee 1991, Greene 1991a, Thorpe 1997, Goldberg 1998, NRC 2002, Greene and Hopson 2003, CBO 2003). These studies yield widely different results concerning not only the magnitude but also the *direction* of the welfare effect, depending on whether they allow for market failure in fuel economy provision or rule it out by assumption. There has been very little attempt to integrate externalities into welfare assessments of CAFE. The one exception is Kleit (2004); using a disaggregated, computational model of the auto market, he estimates that a long-run 3-mpg increase in the CAFE standard would reduce social welfare by \$0.78 per gallon of fuel savings.

Our analysis builds on Kleit (2004) in several respects. We develop detailed estimates of external effects and behavioral responses where prior empirical literature is sketchy. Our framework encompasses a broad spectrum of scenarios about consumers' valuation of fuel saving technologies and their opportunity costs; Kleit's analysis assumed no (nonexternality) market failures. The analytical framework explicitly shows the contribution of underlying parameters to welfare effects; the single vehicle model yields welfare formulas that are easy to implement and update in the light of new evidence, and estimates from the simple model are approximately consistent with those from the multi-vehicle model. We also examine the role of

preexisting fuel taxes, the effect on accidents from changing fleet composition, and we consider a rich array of policy scenarios and sensitivity analysis.³

We summarize the results as follows.

First, we find essentially no difference in the deterioration of emissions per mile over vehicle lifetimes for cars with different fuel economy or for light trucks with different fuel economy. This suggests conventional pollution is (approximately) independent of fuel economy within car and truck groups and varies only with mileage. Overall, tightening CAFE slightly increases pollution because emissions from added driving dominate other behavioral responses; the contribution to overall welfare effects is small, however.

Second, we estimate the marginal congestion cost, averaged across 348 U.S. cities and rural areas, and across time of day, at 6.5 cents per mile. External accident costs per mile are estimated at 4.5 cents per mile for the average passenger vehicle; across the ten vehicle classes, there is little correlation between estimated external accident costs and fuel economy,⁴ hence safety effects of changes in vehicle fleet composition contribute very little to overall welfare effects.

Third, we show that the reduction in fuel demand induced by improved fuel economy is itself welfare improving only if the marginal external costs of carbon emissions and oil dependency exceed the product of the existing fuel tax and the marginal social value of fuel tax revenues. When the social value of an additional dollar of revenue is a dollar, which could be a reasonable approximation even when revenues are earmarked for highways, the reduction in gasoline demand (moderately) reduces welfare because the current (federal and state) fuel tax of

³ Another issue that has been hotly debated is CAFE's impact on highway fatality rates (e.g., Crandall and Graham 1989, Khazzoom 1997, Kahane 1997, van Auken and Zellner 2002, Noland 2004). Our analysis instead quantifies the regulation's effect on external accident costs, which is quite different; external costs exclude own-driver fatality risk, and include nonfatal injuries to other road users, traffic holdups, and a portion of property damage, medical and emergency service costs, and productivity losses (see below).

⁴ This finding is consistent with Miller et al. (1998) and Parry (2004), though the vehicle classes in those studies are far more aggregated.

\$0.40 per gallon overcharges for fuel-related externalities. Our benchmark values for marginal oil dependency and carbon externalities are \$0.20 and \$0.12 per gallon respectively.

Fourth, relative welfare losses from the rebound effect are significant (as in Kleit 2004), though the increase in aggregate mileage is diminished to some extent by the reduction in vehicle sales, which differs depending on how fuel economy technologies and their costs are valued. Although the increase in miles driven is modest, it still causes a substantial welfare cost because mileage-related external costs are large relative to fuel-related external costs. Expressed on a per-gallon equivalent basis at initial on-road fuel economy, marginal external costs from congestion, accidents, and local pollution convert to \$2.53 per gallon, or eight times combined carbon and oil dependency externalities.

Fifth, there is a wide range of possibilities for the welfare change from the improvement in fuel economy itself. A number of engineering studies suggest there are many emerging technologies for which discounted, lifetime fuel savings would easily exceed costs of incorporating them in new vehicles (e.g., NRC 2002, Figure 4.5). Many of these technologies may not be adopted if, as some evidence suggests, consumers care more about other vehicle attributes or if their short time horizons and high discount rates cause them to undervalue fuel savings substantially. In this case, there is a potentially significant welfare gain from regulation that induces manufacturers to adopt such technologies. However, to the extent consumers perceive fuel savings, vehicle manufacturers should incorporate emerging technologies, thereby raising baseline fuel economy and diminishing the effectiveness and welfare gains from higher fuel economy mandates. If consumers correctly perceive fuel savings but value technologies more when used to enhance other vehicle attributes (as in CBO 2003), there is a potentially large welfare loss from fuel economy regulations that divert technologies away from their highest valued use.

Sixth, in the single vehicle model, when fuel savings are correctly perceived a mandated increase of 4 mpg above current levels produces anything from an annual net welfare loss of \$8.89 billion (\$0.73 cents per gallon of discounted fuel saving) to zero effect, depending on whether technologies have high opportunity costs or not. In contrast, if consumers reckon three (rather than 14) years of fuel savings, as many experts in the auto industry believe, there is a net welfare gain of \$2.96 to \$3.95 billion.

Seventh, welfare results from the multi-vehicle model are similar to those from the single-vehicle model: the main difference is that, in aggregate, added vehicle production costs are higher, because the same mpg increase is mandated for cars as a group and trucks even though, due to differential standards, the former have higher marginal compliance costs. Again, whether a tightening of the truck standard alone increases welfare or not depends on how consumers value fuel saving technologies and their opportunity costs.

There are several caveats to our analysis, discussed at the end of the paper: in particular, marginal damages from carbon and oil dependency may change over time, and we do not model possible efficiency gains from induced innovation in the presence of technology spillovers. Nonetheless, given that tightening CAFE standards might have little effect or produce large welfare losses, our own preference would be for alternative policies which appear to have a firmer efficiency foundation, such as broad-based oil and carbon taxes, higher fuel taxes, pay-as-you-drive auto insurance, subsidies for alternative fuel vehicles, and subsidies for R&D into carbon capture technologies.⁵

The rest of the paper is organized as follows. Section 2 develops the single- and multi-vehicle analytical models. Section 3 provides the parameter assessment. Section 4 presents the main results and sensitivity analysis. A final section offers conclusions.

2. Analytical Models

A. Assumptions in the Single-Vehicle Model

(i) *Utility and Driving.* We consider a one-period model where the period represents the average lifetime of a new passenger vehicle, currently 14 years (NRC 2002). At the start of the period the representative agent buys v identical vehicles, drives each of them for m miles, then scraps them at the end of the period.⁶ The agent has utility function:

⁵ See for example Parry and Small (2004), Parry (2005), Leiby and Rubin (2001), Anderson and Newell (2004).

⁶ We treat v as a continuous variable in the household optimization, as it represents the economy-wide vehicle stock.

$$(1a) \quad U = u(D, T, Q, X) - A - O - Z_M - Z_G$$

$$(1b) \quad D = D(v, m, H)$$

$$(1c) \quad Q = qM, M = vm$$

where $u(\cdot)$ is quasi-concave in D , Q , and X and decreasing in T ; all variables are present discounted values per capita.

$D(\cdot)$ denotes sub-utility from vehicle miles traveled; it is increasing and concave in all arguments.⁷ H is government spending on highways; more spending may raise the benefit of driving through access to a more extensive and better-maintained road network. T is in-vehicle time, and $-u_T$ represents marginal disutility from reduced time available for other activities. Q is sub-utility from the quality of vehicle travel and is included to capture trade-offs between fuel economy and other vehicle attributes (e.g., power, comfort, safety, payload); it is equal to vehicle miles of travel (M) scaled by q , a vehicle quality index. Q is defined relative to a reference level (see below) and may be negative. X is the quantity of a numeraire consumption good.

A and O denote, respectively, the social costs of traffic accidents and external costs from the economy's dependence on a volatile world oil market (the nature of the externalities are discussed below). Z_M is environmental damages from local tailpipe emissions subject to emissions per mile regulations. Even though abatement equipment may deteriorate over time, based on empirical findings in Section 3, we assume lifetime emissions are proportional to vehicle miles and independent of fuel economy. Z_G is the cost of emissions that are proportional to fuel use. These include carbon emissions, which are not subject to (federal) emissions per mile regulations, and upstream local emissions leakages from the petroleum industry. A , Z_G , O and Z_M are expressed in utils.

⁷ Concavity in m ensures agents buy more than one vehicle; this may represent increased risk of breakdown for vehicles with higher mileage.

We define:

$$(2) \quad G = gM, \quad p_G = \tilde{p}_G + t_G$$

g and G denote gallons of gasoline per mile (the inverse of fuel economy), and total gasoline consumption, respectively. p_G is the consumer price of gasoline equal to the pre-tax price \tilde{p}_G plus a specific tax per gallon t_G .

The government imposes a maximum allowable ceiling on fuel per mile, \bar{g} , equivalent to a fuel economy standard. The welfare effects of this mandated standard depend on how it reduces fuel per mile relative to the free-market baseline; in practice the latter may decline in future without regulation if emerging fuel saving technologies were to be adopted by the market. To incorporate this we define two reference scenarios: the first (denoted $R1$) represents currently observed fuel per mile inherited from a previous period; the second (denoted $R2$) represents the free-market baseline in the current period after the possible adoption of emerging technologies. Thus:

$$(3a) \quad \left. \begin{array}{l} g^{R2} < g^{R1} \\ g^{R2} = g^{R1} \end{array} \right\} \begin{array}{l} \text{if emerging technologies would be adopted to raise fuel economy} \\ \text{if not} \end{array}$$

$$(3b) \quad \left. \begin{array}{l} g = \bar{g} \\ g = g^{R2} \end{array} \right\} \begin{array}{l} \text{if regulations are binding, } \bar{g} < g^{R2} \\ \text{if not} \end{array}$$

We assume that any preexisting fuel economy standards (in the first reference scenario) are nonbinding, which is a common modeling assumption (e.g., Thorpe 1997, Goldberg 1998, Greene and Hopson 2003, CBO 2003).⁸ To the extent that prior standards might be binding our analysis overstates the welfare effects of mandating higher standards (Kleit 2004).

⁸ A possible justification is that the car standard has been unaltered since 1985 and until a recent ruling the light truck standard had been unaltered since 1995. We also ignore the possibility that firms pay a fine instead of meeting fuel economy requirements, as this has not been the case for U.S. companies.

See www.bts.gov/publications/national_transportation_statistics/2003/html/table_04_23_m.html.

We define:

$$(4) \quad \Gamma = \rho p_G m g$$

Γ is lifetime fuel costs *as perceived by agents at the start of the period*. If $\rho = 1$ agents correctly perceiving future fuel costs (as assumed in CBO 2003, Kleit 2004, Thorpe 1997, and others); we refer to this as the “farsighted consumers” case. If $\rho < 1$ agents undervaluing fuel costs, for example they may have excessive discount rates, consider fuel savings over a shorter horizon than the vehicle lifetime, or it may not pay boundedly rational consumers to inform themselves about fuel costs if they care more about other vehicle attributes (e.g., Greene et al. 2004); we refer to this as the “myopic consumers” case.

(ii) *Externalities*. Travel time is given by:

$$(5) \quad T = \pi M ; \pi = \pi(\bar{M})$$

where $\pi'(\cdot) > 0$ and a bar denotes an economy-wide variable (expressed in per capita terms) perceived as exogenous by individual agents. π is driving time per mile; it increases with aggregate driving as more congested roads slow driving speeds. Agents do not take into account the impact of their mileage on reducing speeds for other drivers.

Accident costs are:

$$(6) \quad A = a_{INT}(M) + a_{EXT}(\bar{M})$$

where $a'_{INT}, a'_{EXT} > 0$. a_{INT} is internalized accident costs (e.g., own-injury risks to drivers) and a_{EXT} is external costs (e.g., pedestrian injuries, property damages not perceived on a per mile basis). Accident costs depend on mileage; below we allow them to also vary with fleet composition.

Remaining external costs are:

$$(7) \quad Z_G = Z_G(\bar{G}); Z_M = Z_M(\bar{M}); O = O(\bar{G})$$

where $Z'_G(\cdot), Z'_M(\cdot), O'(\cdot) > 0$.

(iii) *Firms.* We assume domestic, competitive firms produce gasoline, vehicles, and the numeraire consumption good with labor under constant returns. We believe these are reasonable simplifications for our purposes; Section 5 briefly comments on alternative assumptions.

Manufacturers face the following functions:

$$(8a) \quad C = C(g^{R1} - g), C' = \alpha + \beta(g^{R1} - g)$$

$$(8b) \quad q = q(g^{R1} - g)$$

where α and β are nonnegative parameters. In (8a) $C(\cdot)$ is the added dollar production cost per vehicle from reducing fuel per mile below the first reference level through technology adoption (e.g., technologies to improve engine efficiency and transmission or reduce vehicle drag and rolling resistance); marginal costs are assumed linear. In (8b), we allow for the reduction in fuel per mile to lower quality by diverting technologies that would otherwise have been employed to enhance other vehicle attributes, $q' \leq 0$.⁹

We denote the vehicle sales price by p . Firms' choices over fuel economy affect p and C (see below); however, entry/exit of firms ensure that in equilibrium

$$(9) \quad p = p^{R1} + C$$

where p^{R1} is the vehicle production cost, and equilibrium sales price, in the first reference scenario.

(iv) *Government Budget Constraint.* This is:

$$(10) \quad H + F = t_G G$$

⁹ There is casual evidence that fuel saving technologies may have value in other uses. For example, emerging technologies identified as fuel saving technologies in NRC (1992), including four valve per cylinder engines and four- and five-speed automatic transmissions, were widely introduced over the last decade, yet new vehicle fleet fuel economy did not improve while average horsepower increased significantly (CBO 2002, Table 2).

Besides these opportunity costs there may be other unobserved costs that are excluded from empirical estimates of C , such as marketing, maintenance, consumer unfamiliarity, and retraining of mechanics. However, incorporating them would have essentially the same effect of assuming a lower value for q .

where F is a lump-sum transfer to households. This equation equates highway and transfer spending with fuel tax revenues. We consider cases where changes in revenues imply either changes in H or F .

B. Solution to the Single-Vehicle Model

(i) *Household Optimization.* We solve the household optimization problem backwards in two steps (this is necessary when agents misperceive lifetime fuel costs). First, for a given number of vehicles \tilde{v} purchased at the start of the period, households choose miles per vehicle and the numeraire good to maximize utility (1) subject to the budget constraint $I + F - p\tilde{v} = X + \tilde{v}p_G m g$ and (5)–(7), where I denotes (fixed) labor income.¹⁰ Second, at the start of the period they optimize over the number of vehicles and (planned) spending on the numeraire good, subject to the constraint $I + F = X + v(p + \Gamma)$, (5)–(7), and taking Γ as given.

The optimization yields:

$$(11a) \quad \{u_D D_m / v + u_T \pi - a'_{INT}\} / u_X = p_G g + \omega / m$$

$$(11b) \quad \{u_D D_v / m + u_T \pi - a'_{INT}\} m / u_X = p_E$$

$$(11c) \quad p_E \equiv p + \Gamma + \omega$$

where $\omega(q^{R1} - q) = u_Q(q^{R1} - q)m / u_X$ is the utility loss (in dollars) from reduced quality per vehicle ($\omega' > 0$). Equation (11a) equates driving benefits per mile, net of time and internal accident costs, with per mile costs of fuel and reduced travel quality. Equation (11b) similarly equates driving benefits per vehicle, net of time and internal accident costs, with “effective” vehicle price p_E ; the latter includes the sales price, perceived lifetime fuel costs, and quality costs.

¹⁰ We assume agents correctly perceive fuel costs when choosing mileage, as this is an ongoing decision (unlike the vehicle purchase decision that requires forecasting over a 14-year period).

To obtain demand functions we assume changes in π and a'_{INT} are negligible (this is reasonable as proportionate changes in M are small) and that m is unaffected by changes in vehicle quality.¹¹ We also adopt constant-elasticity functional forms:

$$(12a) \quad m \approx m^{R1} \left\{ \frac{g}{g^{R1}} \right\}^{\eta_m}$$

$$(12b) \quad v \approx v^{R1} \left\{ 1 + \frac{p_E - p_E^{R1}}{p^{R1}} \right\}^{\eta_v}$$

$\eta_m < 0$ 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 the effective price.¹²

(ii) *Firm Optimization.* From (11b) firms face a sales price $p = p_E - \Gamma - \omega$; they take p_E as given as they are competitive, though their choice of fuel economy alters how much consumers are willing to pay for vehicles p , through altering Γ and ω . With no fuel economy constraint firms choose g to maximize profits per vehicle $p - (C + p^{R1})$. Using (4) and (8), this yields:

$$(13) \quad \rho mp_G = C' + \omega'q' \rightarrow g^{R2} = g^{R1} - \{\rho mp_G - (\alpha + \omega'q')\} / \beta$$

Equation (13) states that fuel per mile is reduced until the incremental lifetime fuel saving benefits perceived by consumers, ρmp_G , equals the added vehicle cost, C' , plus the marginal value of forgone vehicle quality, $\omega'q'$.

Since forgone quality is unobservable, $\omega'q'$ is assumed constant, and we consider cases to span the range of possibilities for its magnitude. In a “no opportunity costs” scenario (e.g., NRC 2002), we simply set $\omega'q' = 0$. In an “opportunity costs” scenario, we follow CBO (2003) and assume any failure to adopt emerging technologies for which perceived fuel saving benefits exceed added vehicle costs, is explained entirely by forgone quality.

¹¹ Thus, we ignore a possible counteracting effect on mileage due to the potential for fuel economy improvements to reduce driving quality; the assumption is made because empirical evidence is unavailable to quantify this effect.

¹² We define changes in effective prices relative to the retail price in order to apply elasticities from the empirical literature that are defined relative to retail prices.

Thus, there are four possible equilibria in the second reference or baseline scenario, illustrated in Figure 2. With farsighted consumers, equilibrium is at point A, with opportunity costs, and point B, with no opportunity costs. Since the perceived and actual (or social) marginal benefits are the same, and equal to marginal cost, inclusive of any opportunity costs at these points, any mandated reduction in fuel per mile beyond these levels will reduce efficiency (leaving aside externalities and fuel taxes). With myopic consumers, equilibrium is at point C, with opportunity costs, and point D, with no opportunity costs. In these cases, a mandated reduction in fuel per mile can increase efficiency, because the social marginal benefit initially lies above marginal costs (inclusive of any opportunity costs). Finally, note that in the no opportunity cost cases, standards must be increased above a strictly positive threshold level before they become binding and have any effect.

(iii) *Welfare Effects.* When regulation is binding ($\bar{g} < g^{R2}$), the (monetized) welfare effect (denoted W) 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 the following three components (see Appendix):

$$(15a) \quad -\frac{dW}{d\bar{g}} = \overbrace{(\beta t_G - E_G)}^{\text{gasoline reduction}} \left\{ -\frac{dG}{d\bar{g}} \right\} - \overbrace{E_M}^{\text{mileage increase}} \left\{ -\frac{dM}{d\bar{g}} \right\} + \overbrace{\{mp_G - (C' + \omega'q')\}}^{\text{fuel economy}} v$$

$$(15b) \quad E_G = (Z'_G + O')/u_X; \quad E_M = \{a'_{EXT} + Z'_M - u_T M \pi'\}/u_X; \quad \beta = \left\{ \frac{dF}{dG} + \frac{dH}{dG} \frac{u_H}{u_X} \right\} \frac{1}{t_G}$$

$$(15c) \quad \frac{dG}{d\bar{g}} = M + \bar{g} \frac{dM}{d\bar{g}} > 0; \quad \frac{dM}{d\bar{g}} = v \frac{dm}{d\bar{g}} + m \frac{dv}{dp_E} \frac{dp_E}{d\bar{g}} < 0$$

E_G is the external cost per gallon (in dollars) from carbon emissions, upstream local emissions, and oil dependency. E_M is the external cost per mile from accidents, local tailpipe pollution, and congestion.¹³ β is the social value per dollar of tax revenue. If all marginal revenue is spent on

¹³ The marginal cost of congestion is the increase in travel time per mile following an incremental increase in aggregate mileage π' , times per capita mileage M , times the marginal disutility of in-vehicle time, $-u_T$.

transfer payments, $dF/dG = t_G$ (from (10)) and $\beta = 1$. If it is all spent on highways, $dH/dG = t_G$ and $\beta = u_H/u_X$; in this case β is greater/less than unity if the value of an extra \$1 of highway spending is greater/less than \$1. We assume E_G , E_M , and β are constant.¹⁴

The first component in (15a) is the induced welfare change in the gasoline market. It equals the change in gasoline times the product of β and the gasoline tax, minus the per gallon external cost. If $\beta = 1$, the reduction in gasoline increases/decreases welfare, depending on whether the gasoline tax under- or over-charges for external costs of fuel use. With fuel tax revenues earmarked for highways, the erosion of the fuel tax base involves higher/lower efficiency costs (gross of externalities) if the social value per \$1 of marginal government spending is greater/less than \$1. Thus, the common perception that fuel taxes are not distortionary because they pay for highways is only valid in our analysis if highway spending has no social value.

The second component in (15b) is a welfare loss equal to the increase in mileage, or “rebound effect,” times the external cost per mile from mileage-related externalities. The increase in mileage equals the increase in miles per vehicle due to lower per mile costs, less a (partially) offsetting effect due to reduced vehicle demand as the effective vehicle price increases, as in (12a), (14) and (15c); note that the change in effective price will vary with the different scenarios in Figure 2.¹⁵

The third welfare component is from the increase in fuel economy itself. It is the marginal social benefit from fuel savings, net of marginal vehicle costs, including forgone quality, times the number of vehicles. As can be seen in Figure 2, there is a welfare loss with farsighted consumers, but a potential welfare gain with myopic consumers.

¹⁴ These are reasonable assumptions with the possible exception of marginal oil dependency costs, which vary modestly with reductions in oil use (Leiby et al. 1997).

¹⁵ The effective price always increases because marginal costs, including quality costs, exceed perceived marginal benefits, for nonincremental reductions in fuel per mile beyond the free market baseline (see Figure 2). In our simulations below, the reduction in vehicle sales lowers the rebound effect by between 14 and 26% across different scenarios.

Equation (15a) is easily integrated to obtain welfare effects of nonincremental policy changes, using Equations (8a), (12), assumptions about opportunity costs, and parameter values discussed below.

C. Multi-Vehicle Model

We now assume the representative agent drives $i = 1 \dots N^C$ cars and $i = N^C + 1 \dots N^T$ light trucks; we maintain the assumption of homogeneous firms, where each firm is engaged in production of all vehicles. Initial prices, fuel economy, and the marginal cost of reducing fuel use per mile differ across vehicles, as do accident and pollution costs per mile, though not congestion costs.¹⁶ Added vehicle production cost and quality take the same form as in (8). Vehicle demands are now given by the constant elasticity formulas:

$$(16) \quad v_i = v_i^{R1} \prod_{j=1}^{N^T} \left\{ 1 + \frac{P_{Ej} - P_{Ej}^{R1}}{P_j^{R1}} \right\}^{\eta_{ij}}, \quad i, j = 1 \dots N^T$$

where η_{ii} is an own-price elasticity and η_{ij} ($j \neq i$) a cross-price elasticity.

CAFE sets separate standards for the harmonic average miles per gallon across car and light-truck fleets; this 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:

$$(17) \quad \sum_{i=1}^{N^C} (\bar{g}^C - g_i) v_i = 0, \quad \sum_{i=N^C+1}^{N^T} (\bar{g}^T - g_i) v_i = 0$$

Manufacturers choose fuel per mile for each vehicle, and vehicle sales, to maximize profits $\sum_{i=1}^{N^T} \{p_i - (C_i + p_i^{R1})\} v_i$ subject to (11c), (16) and (17), taking p_{Ei} as given. This yields:

$$(18a) \quad C'_i + \omega'_i q'_i - \rho p_G m_i = \delta_k, \quad i = 1 \dots N^C, \quad k = C; \quad i = N^C + 1 \dots N^T, \quad k = T$$

$$(18b) \quad p_i - (C_i + p_i^{R1}) = \delta_k (g^i - \bar{g}^k), \quad i = 1 \dots N^C, \quad k = C; \quad i = N^C + 1 \dots N^T, \quad k = T$$

¹⁶ FHWA (1997), Table V-23, puts the difference in marginal congestion costs across cars and light trucks at only 0.01 to 0.15 cents per mile; vehicles differ in length, and therefore how much road space they take up, but these differences are small relative to average on-road distance between vehicles.

δ_C and δ_T are the shadow prices on the constraints for cars and trucks respectively; prior to any mandated increase in fuel economy $\delta_C, \delta_T = 0$.

Equation (18a) states that within a vehicle class (cars or trucks) fuel economy is improved in a vehicle until the increased production and quality cost, net of perceived fuel saving benefits, is equated to the shadow price of the fuel economy constraint for that class. (18b) states that, within a vehicle class, sales prices are above, equal to, or below production costs, according to whether fuel per mile is above, equal to, or below the average for that class, when the standard is binding. Thus, the standard effectively taxes fuel inefficient vehicles and subsidizes fuel efficient ones. By altering the relative vehicle prices in this way, the multi-vehicle model admits another channel for improving fleet average fuel economy that is absent from the single-vehicle model.

External costs of fuel consumption are identical for cars and trucks (though per mile costs differ); thus, there is no efficiency rationale in our analysis for policies resulting in different shadow prices on fuel economy for cars and trucks.¹⁷ If fuel economy credits could be traded across cars and light trucks this would effectively replace the separate standards with a single standard and a single shadow price; efficiency would improve in two respects. First, the marginal cost of improving fuel economy, including quality costs, and net of perceived fuel savings, would be equated across all vehicles, rather than differing between cars and trucks; second, the penalty (subsidy) for a vehicle with relatively high (low) fuel per mile would be the same for cars and trucks.

The multi-vehicle model is solved in a spreadsheet that selects values for the shadow prices, uses these to compute fuel economy and vehicle sales prices from (18), and then vehicle demands from (16), and then iterates over the shadow prices until constraints in (17) are met for given fuel economy standards.

Analogous to the decomposition in (15a), the welfare change from a nonmarginal policy change is calculated by:

¹⁷ When CAFE standards were initially introduced light trucks were mainly used for industrial and agricultural purposes and a lower standard for them was set to limit the burden on commerce. Today however, today most light trucks are used as passenger vehicles.

$$(19) \Delta W = \underbrace{(\beta t_G - E_G)(G^{R2} - G)}_{\text{gasoline reduction}} - \underbrace{\sum_{i=1}^{N^T} E_{Mi}(M_i - M_i^{R2})}_{\text{mileage increase}} + \underbrace{\sum_{i=1}^{N^T} \{p_G [g_i^{R2} m_i^{R2} - g_i m_i] - [C_i(g_i) - C(g_i^{R2})] - \omega'_i q'_i (g_i^{R1} - g_i)\} (v_i^{R2} + v_i)}_{\text{fuel economy}} / 2$$

3. Benchmark Parameter Values

Here we discuss benchmark parameter values; in a subsequent sensitivity analysis we consider alternative values for key parameters.

A. Basic Vehicle Data

Table 1 summarizes vehicle classifications, sales, initial prices, fuel economy, and actual lifetime fuel costs for model year 2000; this data is used to produce the first reference scenario.

Following Chapter 4 of NRC (2002), we distinguish four car classes (subcompact, compact, midsize, and large) and six light truck classes (small SUV, mid SUV, large SUV, small pickup, large pickup, and minivan). Cars and light trucks each account for about 50% of total passenger vehicle sales. Initial certified fuel economy averages 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% of the certified level.¹⁸

Following NRC (2002) we assume all vehicles are initially driven 15,600 miles in the first year, decreasing thereafter at 4.5% per year, over the 14-year life cycle. Initial discounted

¹⁸ See NRC (2002), p. 66. Unlike certified (i.e. dynamometer-tested) fuel economy, on-road fuel economy varies with traffic conditions, temperature, trip length, frequency of cold starts, driving style, etc. Certified fuel economy is from NRC (2002), Table 4.2 (adjusted for future safety and emissions standards). As in NRC (2002), we assume no deterioration of fuel economy over vehicle lifetimes. Sales data was compiled from *Wards Automotive Handbook 2001*. The price for each vehicle class was obtained from a sales-weighted average of prices of models within that class 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 some other specialty vehicles like hybrids were excluded.

lifetime fuel costs for vehicle i , $m^{R1} p_G g^{iR1}$ are therefore computed with $m^{R1} = 15,600 \sum_{j=1}^{14} 1/(1+r^S + .045)^{j-1}$, where r^S is a social discount rate. We assume $r^S = 0.05$, a typical value used in medium-term cost–benefit analysis.¹⁹ The retail gasoline price, p_G , is \$1.50 per gallon.²⁰

A widely cited econometric analysis by Dreyfus and Viscusi (1995) estimated that consumers discount gasoline costs at between 11 and 17%, which would imply $\rho = 0.78$ and 0.64 respectively.²¹ Many people in the auto industry believe that new vehicle buyers only consider fuel costs over the first three years, and this is the assumption built into the U.S. Energy Information’s National Energy Modeling System (Greene et al. 2004); this would imply $\rho = .33$, which we adopt for the myopic consumers case.

B. Cost of Improving Fuel Economy

We calibrate the direct costs of improving fuel economy ΔC_i to underlying data in NRC (2002);²² this yields coefficients shown in the last two columns of Table 1 (for $g^{R1i} - g^i$ in gallons per 100 miles). Marginal costs rise more rapidly for smaller vehicles with higher initial fuel economy. The benefit from a gallon reduction in gasoline per 100 miles, evaluated at the

¹⁹ See for example www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html.

²⁰ This is an average over the previous decade. See www.eia.doe.gov/emeu/international/gas1.html.

²¹ A possible explanation for discount rates exceeding market rates is that auto buyers are liquidity constrained; Ozazio et al. (2000) find some evidence for this for younger and middle income households. The above finding is consistent with evidence that consumer discount rates for a wide spectrum of energy saving appliances exceed market interest rates (Frederick et al. 2002).

²² Their data consist of costs and fuel savings from a wide range of technological options for each vehicle type, which we order by the ratio of average cost to the average percentage improvement in fuel economy. Fitting regressions of the form in (8a) to this data yields our coefficient estimates. The NRC estimates were obtained from available evidence and conversations with manufacturers, and are broadly similar to those in a number of other engineering studies (see NRC 2002, figures 4.5 and 4.6). Cost estimates are expressed as retail price equivalents with a 40% markup assumed for parts supplier, automaker, and dealer. Thus, costs may be overstated, since some of the markup may reflect a transfer payment rather than a pure resource cost.

social discount rate and first reference mileage, is \$1,940 for each vehicle; this greatly exceeds all the intercepts of all the marginal cost curves.

C. 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 vehicle price elasticities.²³ However the magnitude of the own-price elasticities are too large as they reflect people holding on to used vehicles longer—an effect that disappears in the long run—in addition to substitution between vehicles and reduced overall vehicle demand; the own-price elasticities are therefore adjusted as follows.

First, 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 $\hat{\eta}_{TT} = -0.85$.²⁴ Second, we express the own-price elasticity for car i computed from the GM model as $\eta_{ii} = \sum_{j \neq i} \eta_{ji} x_j / x_i + (\eta_{ii} - \sum_{j \neq i} \eta_{ji} x_j / x_i)$, where $i, j = 1 \dots C$. The first component reflects substitution effects among cars. The second component encompasses all other effects—reduced overall vehicle demand, substitution into trucks, and people holding on to vehicle i longer; to remove the last effect we scale 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 . Truck elasticities are similarly

²³ The GM model estimates sales of specific vehicle models, given a set of prices for all included models, for model year 1999. We aggregate these responses to estimate changes in demand for each new vehicle class, according to the percentage change in its own price and those of the other new vehicles.

²⁴ The Harrington et al. model incorporates a nested logit structure of household ownership over new and old cars and light trucks where the demarcation between new and old vehicles is 3.5 years. The nesting structure consists of an upper level where the choice of how many vehicles to own is estimated and a lower level where vehicle class/vintage is estimated; vehicle miles traveled is then estimated conditional on the number of vehicles owned. Behavioral response parameters are econometrically estimated from the 1990 National Personal Transportation Survey (NPTS), and initial conditions calibrated to match the observed 2001 vehicle fleet composition. The above elasticities were obtained from increasing new car prices by 1% and running the model through 30 years and similarly for light trucks.

scaled using $\hat{\eta}_{CC} / \tilde{\eta}_{CC}$, where $\tilde{\eta}_{TT} = -0.97$. Results shown in Table 2: own-price vehicle elasticities vary between -1.40 and -3.20 .

For the single vehicle model we assume a vehicle demand elasticity η_v of -0.36 , based on the long run change in car and truck demand to a 1% increase in all vehicle prices that we estimated using the Harrington et al. (2003) model.²⁵ And we assume a miles per vehicle elasticity $\eta_m = 0.15$.²⁶

D. Local Pollution Costs

(i) *Tailpipe emissions and fuel economy.* First, we validate our assumption that local tailpipe emissions are independent of fuel economy within car and light truck classes.

If there were no deterioration over time of abatement equipment installed in new vehicles to satisfy a given emissions per mile standard, improving a vehicle's fuel economy would have no effect on its lifetime per mile emissions rate. However, because abatement equipment deteriorates over time, and vehicles with lower fuel economy have greater engine-out emissions (i.e. emissions into the catalytic converter), it is conceivable that tailpipe emissions will be negatively related to fuel economy in used vehicles. Indeed, Harrington (1997) identified this negative relation, by mapping remote sensing data on vehicle emissions in 1990 from the Arizona Inspection and Maintenance (I/M) Program to EPA-certified fuel economy data. However these results need to be revisited because current motor vehicles have more durable control equipment than the 1990 fleet, and even if the negative relation persists it may have lost its practical significance given the rapid decline in new vehicle emission rates since 1990.

²⁵ In contrast, aggregate vehicle demand falls by 1.2% following a 1% increase in all vehicle prices in the GM model, which is consistent with other short-run estimates (e.g., McCarthy 1996, p. 543).

²⁶ In recent time series the estimated elasticity of vehicle miles with respect to fuel costs is around -0.1 in the short run, increasing to -0.2 or more over the long run; results from studies using cross-sectional survey data are more variable (see Greene et al. 1999 and Small and van Dender 2004 for more discussion). In the Washington-START model described below the mileage elasticity is -0.14 . These estimates understate the magnitude of η_m somewhat as they are net of the reduction in vehicle demand.

We repeated Harrington's analysis of deterioration rates using data from the Arizona I/M program collected in 1995 and 2002 on car and truck emissions of volatile organic compounds (VOC), nitrogen oxides (NO_x), and carbon monoxide (CO).²⁷ The 1995 dataset showed that emission rates were still significantly affected by fuel economy (though less so than in 1990); however we were unable to find much of an effect in the 2002 dataset.²⁸ As shown in Figure 3, projected CO, hydrocarbon (HC) 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.²⁹ Thus it seems reasonable to assume lifetime emission rates are equivalent for different cars and for different light trucks.

(ii) *Per mile tailpipe emission 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), 0.19 cents per gram for VOC, 0.69 cents per gram for NO_x, and zero for CO,³⁰ and aggregate over pollutants. The result is external damages of 1.1, 2.0, and 1.5 cents per mile for cars, light trucks, and all vehicles respectively.

²⁷ 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). The test itself changed between these dates; however, we were able to transform 1995 test results into 2002 test results using a procedure developed by Sierra Research (2003).

²⁸ We used a Davidson-MacKinnon (1981) test to compare a simple model of emissions deterioration based on mileage versus one based on fuel economy. The fuel economy model performed better in five out of six vehicle/pollution groups in 1995. In 2002 the superiority of the fuel economy model is limited to car HC and CO; in other cases the mileage model does as well or better. Statistical results are available from harrington@rff.org.

²⁹ The graphs in Figure 3 were obtained through regressing emissions on fuel economy for vehicles of a given age, and reading off emissions from this relation at mpgs of 20 and 30.

³⁰ See their Table 5, "baseline assumptions". Damages are dominated by mortality effects; we scale estimates to be consistent with the value of life for traffic fatalities assumed below. Small and Kazimi's estimates are on the high side as they apply to Los Angeles (rather than the nation as a whole), where the topography tends to trap pollutants and the climate favors photochemical reactions.

(iii) *Upstream emissions leakage*. The most important pollutant emitted during the activities of petroleum production, refining, transport and storage is VOCs. In 1999, petroleum industry VOC emissions amounted to 9.8 grams per gallon;³¹ using our damage estimate gives 1.9 cents per gallon.

E. Global Pollution Costs

Most economic assessments of the damages to future world agriculture, forestry, coastal activities, and so on, from carbon emissions put damages at well below \$50 per ton of carbon (Tol et al. 2000, Pearce 2003). A few studies obtain much higher values by attaching differing distributional weights to rich and poor nations (the latter being the most at risk from climate change) and assuming zero rates of time preference (e.g., Tol 1999). The possibility of abrupt, nonlinear climate change may also be understated in conventional damage assessments (Schneider 2004). We follow NRC (2002) in adopting a benchmark value of \$50 per ton and consider other values later; since a gallon of gasoline contains 0.0024 tons of carbon (NRC 2002) this converts to 12 cents per gallon.

F. Congestion Costs

We are unaware of previous estimates of nationwide marginal congestion cost (MCC).³² To obtain an estimate we begin with a model of the Washington, DC, metropolitan area road

³¹ Calculated from EIA (2002) and EPA (1999), Appendix A-5. The emissions rate has fallen by 64% since 1980 due, at least in part, to increased regulatory stringency.

³² Schrank and Lomax (2002) estimate average congestion costs per mile for 75 U.S. cities. However, MCCs are highly convex with respect to traffic volumes under congested conditions, so it is difficult to infer MCC from average costs, even if we had estimates for all 348 cities. Moreover, in deriving MCCs averaged across time of day, we need to account for the weaker sensitivity of peak-period driving to fuel costs than off-peak driving; the former is dominated by commuting, and fuel costs are a smaller portion of combined time and money costs of driving. Furthermore, in computing MCC, account should be taken of various re-allocations of travel across peak and off-peak periods, and across roads with different degrees of congestion within a period, as the pattern of driving and congestion changes (Yang and Huang 1998); this requires a network model.

network, Washington-START.³³ Fuel economy is a parameter input into the model that affects per mile driving costs. We increase this parameter incrementally and calculate the change in consumer welfare, after netting out fuel savings. This gives an estimate of net welfare change from added congestion and utility of the additional trips taken by motorists. Dividing by extra aggregate mileage we obtain an MCC of 7.7 cents per mile.

We extrapolate a nationwide MCC estimate as follows. We compute MCCs from the Washington-START model with the baseline population and travel demand scaled by between +20% and -40%, holding the road capacity fixed; results are used to estimate a relation between MCC and the mileage/pavement ratio (R), where R is normalized to unity for Washington. We then inferred values for MCC for the 75 cities for which R can be obtained from Schrank and Lomax (2002), using our MCC/ R relation. These 75 cities are then classified into four bins according to their population and an average of MCCs for each bin is then obtained: MCCs vary between 7.3 cents per mile for cities with over 3 million population to 2.2 cents per mile for cities with 100,000 to 500,000 population. We attribute one of these four MCC values to the remaining 273 cities using population figures from the Census Bureau. Finally, we aggregate MCCs over all cities using the shares of total U.S. population within each city class, and assuming MCC for areas outside cities is zero. The result is a nationwide MCC of 6.5 cents per mile.³⁴

G. External Accident Costs

We follow the methodology in Parry (2004) to estimate external accident costs per mile for the ten vehicle types.

³³ In the model, households have a nested logit utility function and optimize over trips, destination, mode, time of day, and route. Forty travel zones are disaggregated with arterials and side streets within each zone aggregated into an in-bound, out-bound, and circumferential link; freeway segments and bridges are also incorporated. The distribution of travel and the speed/traffic flow curves are taken from the Metropolitan Washington Council of Governments' transportation planning model. Behavioral responses to travel costs at different times of day are calibrated to estimates in the travel demand literature. See Safirova et al. (2004) for more discussion of the model.

³⁴ This figure is for the costs of recurrent congestion. Nonrecurrent congestion due to accidents is incorporated below; congestion from roadworks and bad weather is excluded.

Crash data averaged over 1998–2000 is used to assign traffic injuries to different vehicle types.³⁵ 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. However, whether other occupant injuries are external is unclear; all else being the same, one extra vehicle on the road raises the accident risk for other drivers, but if people drive slower or more carefully in heavier traffic, a given accident will be less severe. We assume 50% of other occupant injuries are external.

Traffic delay, property damage, and miscellaneous costs (medical costs, emergency services, and legal/court costs) are divided equally among vehicles in the crash. We assume 100% of travel delay costs, 85% of miscellaneous costs (which are mainly covered by group insurance), and 75% of property damages are external.³⁶ We use estimates from NHTSA (2002b), Table A-1, to value quality of life costs, property damage, travel delay, and miscellaneous 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.³⁷

Overall, the mean external cost is 4.39 cents per mile (Table 3). Pedestrian injuries account for 18% of costs, other driver injuries 37%, property damage 7%, travel delay 4%, and

³⁵ 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), p. 18, we scale up nonfatal injuries by 12% and 9% 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*).

³⁶ 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 moderately, with previous crash record and stated annual mileage.

³⁷ Mileage shares for vehicle classes were obtained from the NPTS, weighting results from the 1995 and 2001 surveys by one-third and two-thirds respectively. Total mileage per vehicle class was obtained by multiplying these shares by economy-wide annual passenger vehicle mileage, averaged over 1998–2000, of 2.5 trillion (from www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSFAnn/TSF2000.pdf).

miscellaneous costs 34%. External costs are moderately higher than average for pickups and subcompacts, and below average for minivans, midsize cars, and small SUVs. In part these differences reflect ownership concentrations: small cars are disproportionately owned by young, inexperienced drivers, who have greater propensity to drink and drive, while minivans and SUVs are disproportionately owned by drivers with children who are likely to take more care on the road. Crudely adjusting for driver age removes some though not all of the disparities (Table 3, bottom row).³⁸ For example, small cars still have higher than average costs, partly because they include sports cars, which are driven more aggressively; pickups also have relatively high costs as they do more damage to other road users in a collision and may crash more frequently if drivers feel safer in them compared with cars.

H. External Costs from Oil Dependency

Most estimates focus on two main components. First is the “optimum tariff” component, determined by the inverse import supply elasticity; this depends on the U.S. share of world oil consumption and how OPEC, and other oil exporting and importing regions, might respond to a change in U.S. import. Second is the expected cost of economic disruptions during price shocks that the private sector may not fully anticipate or be insured against. These include added payments for imports and various adjustment costs (e.g., temporarily idled capital and labor); they are estimated using postulated probability distributions for price shocks or supply disruptions, estimated oil price-GDP elasticities, and assumptions about how markets internalize oil price risks. Recent estimates for these two components combined vary between \$0 and \$14 per barrel, or 0 to 33 cents per gallon;³⁹ NRC (2002) adopted a value of 12 cents per gallon. However we use a benchmark value of 20 cents, to allow for probable increases in the long-run

³⁸ To make this adjustment, we first compute external costs per mile relative to the mean external costs for under 25, 25–70, and over 70 age groups from our data: relative costs are 2.47, 0.78, and 1.23, respectively. Using mileage shares across these age groups for each vehicle type obtained from the NPTS, we divide external costs for that vehicle by the mean risk factor for drivers of that vehicle.

³⁹ See the seven studies summarized in CEC (2003), Table 3.12. Leiby et al. (1997) is a particularly comprehensive assessment.

oil price since 2002, elevated risks of regional conflict, and terrorist attacks on oil infrastructure in the Persian Gulf.⁴⁰

I. Government Parameters

The gasoline tax is 40 cents per gallon.⁴¹ Initially, we assume $\mu = 1$; that is, all marginal spending is transfers, or the social value per \$1 of highway spending is \$1. The latter may not be unreasonable: Shirley and Winston (2004) estimate annual returns from highway investments at around 5%, our assumed social discount rate. If instead the rate of return on highway spending were say 30%, then $\mu = 1.24$.

4. Results

A. Single-Vehicle Model

(i) *Benchmark Results.* Table 4 displays benchmark results from the single-vehicle model for an increase in fuel economy from the currently observed (first reference) level of 24 mpg to 28 mpg.

With farsighted consumers and no opportunity costs (initially point B in Figure 2) there would be a large market-determined increase in fuel economy up to 30.8 mpg in the second

⁴⁰ Assuming the long run oil price has increased from around \$25 (at the time of the NRC study) to \$30 per barrel would add about 2 cents. Based on personal communication with Paul Leiby we add another 6 cents to account for political and terrorist risks, though this is highly subjective.

Middle East military expenditures have been quantified at around \$50 billion per year, or \$7 per barrel of oil (www-cta.ornl.gov/data/Download23.html, Table 1.9). Although these costs might apply to an estimate of *total* external costs, they are usually excluded from marginal costs because they are regarded as a fixed cost that would not fall following a moderate reduction in US oil consumption.

A further point is that although the potential market power of OPEC is substantial (e.g., Greene 1991b), this does not in itself add to any distortion between marginal consumer benefit and marginal supply cost in the US oil market, and therefore does not directly add to marginal external costs.

⁴¹ 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).

reference scenario; hence a tightening of the standard up to 28 mpg is nonbinding and has no effect at all.

With opportunity costs (second column, Table 4), fuel economy would remain at 24 mpg in the absence of regulation (point A in Figure 2). A tightening of the standard by 4 mpg reduces discounted lifetime fuel consumption by 12.1 billion gallons, or 13.0%; this reduces welfare by \$0.74 billion, given that the fuel tax (\$0.40 per gallon) exceeds combined external costs from carbon, oil dependency, and upstream emissions leakage by \$0.06 per gallon. Miles driven increases by “only” 1.5%; however the resulting welfare loss is a substantial \$3.43 billion. The reason is that mileage-related externalities are relatively large in magnitude; at initial fuel economy, they convert to \$2.53 per gallon.⁴² There is another large welfare loss of \$4.72 billion from the improvement in fuel economy itself. In sum, welfare losses amount to \$8.89 billion, or \$0.73 per gallon of fuel saved.

With myopic consumers and no opportunity costs (initially point D in Figure 2) fuel economy would increase to 25.7 mpg without regulation (third column of Table 4). Welfare losses from reduced gasoline and increased mileage are therefore smaller than when second reference fuel economy remains at 24 mpg. However the increase in fuel economy itself now generates a welfare gain of \$5.88 billion, given that the marginal social benefit from reducing fuel per mile exceeds the marginal vehicle cost (fuel savings are \$10.76 billion and these outweigh added production costs of \$4.88 billion). Overall, there is a welfare gain of \$2.96 billion, or \$0.47 per gallon of fuel saved.

Finally, with myopic consumers and opportunity costs (initially point C in Figure 2), there is an overall welfare gain of \$3.95 billion, or \$0.33 per gallon of fuel savings.

(ii) Sensitivity Analysis. Figure 4 illustrates effects of varying various parameters one at a time. Results are moderately sensitive to varying fuel-related external costs, mileage-related external costs, the mileage elasticity, the value per \$ of government spending, and the price of gasoline. In each of these sensitivity analyses, the finding that higher fuel economy improves welfare in

⁴² Kleit (2004) and Lutter and Kravitz (2003) also emphasize the large welfare loss from the rebound effect, though using different parameter assumptions to those above.

the myopic consumer scenarios has no effect in the farsighted consumers/no opportunity cost scenario, but substantially reduces welfare in the farsighted consumers/opportunity cost scenario is generally robust. Finally, in the lower right panel we vary the level of the standard: maximum welfare gains in the myopic consumer cases are approximately \$4 billion and reached at fuel economy increases of around 4 to 6 mpg.

B. Multi-Vehicle Model

In aggregate, results from the multi-vehicle model using benchmark parameters are similar to those in the single vehicle model (see Table 5). The main difference is that production costs are around 20 to 35% larger, due the extra distortion caused by the differential car and light truck standard; the standard is raised by the same amount for cars as a group as for trucks, even though marginal costs of improving fuel economy for cars are significantly greater. Overall, welfare effects vary from \$1.44 billion in the myopic/no opportunity cost scenario to -\$12 billion in the farsighted/opportunity costs scenario. Another difference is that welfare losses from the mileage effect are around 40% larger in the far-sighted/no opportunity costs scenario; this reflects a smaller offsetting effect from the change in vehicle sales.

In Table 6 we raise the light-truck standard by 6.8 mpg up to the current car standard of 27.5 mpg; the upper and lower halves of the table illustrate cases with and without trading of credits across cars and trucks. Either way, qualitative results are similar to those above; there is no effect in the farsighted/opportunity cost scenario, substantial welfare losses in the farsighted/opportunity costs scenario, and moderate welfare gains in the two cases with myopic consumers.

Finally we note two other results that apply to all policy scenarios in the multi-vehicle model (but are not illustrated in Tables 5 and 6). First, allowing for external accident costs to vary across vehicles has only a negligible effect; welfare losses from the mileage effect fall by only about 1% across the different scenarios. This reflects the relatively modest differences in external costs across vehicles and the weak correlation between fuel economy and accident costs. Second, on net higher fuel economy standards increase local pollution emissions, resulting in

welfare losses of around \$0.25 to \$0.45 billion across the different scenarios; this is because pollution costs from added driving dominate other behavioral responses.

5. Conclusion

Based on our best assessment of parameter values, it appears to be difficult to justify tightening car and light truck fuel economy standards on externality grounds alone (see also Kleit 2004). The key reason for this result is that external costs from carbon emissions and oil dependency estimates in other studies are small in magnitude relative to external costs that increase through the rebound effect; they even fall short of current fuel taxes. Higher fuel economy standards may moderately improve welfare if there is an additional market failure due to consumers substantially undervaluing fuel savings, and fuel-saving technologies have little value in alternative uses; however there is no firm consensus among analysts on the magnitude of this additional market failure.

There are a variety of caveats to our analysis. It is easy to imagine future scenarios with higher (marginal) costs of oil dependency: a political takeover in Saudi Arabia (the swing producer) by elements hostile to the United States; heightened risks of terrorist attacks on oil infrastructure; greater abuse of market power as world oil production becomes more concentrated in the Persian Gulf; rapid growth in vehicle ownership in China and India adding to oil market pressures. On the other hand, market penetration of hybrid and alternative fuel vehicles, and enhanced supply from conventional oil finds or breakthroughs in converting oil-bearing formations (oil shales and tar sands), may lower future concern about oil dependency. Perceived costs of greenhouse gases may change with improved knowledge about the extent of global warming and the likelihood of abrupt, nonlinear climate change. The costs of the rebound effect may increase if marginal congestion costs continue to rise or fall as fuel costs diminish relative to driving time costs. All these uncertainties underscore the need for frequent updating of the analysis.

Allowing for increasing returns and strategic behavior among manufacturers could alter CAFE's impact on vehicle prices and sales and would introduce a wedge between vehicle price and marginal production cost. It is unclear whether this would have a major impact however,

given that welfare effects depend primarily on changes in fuel economy, gasoline, and miles driven, rather than changes in vehicle sales.

We ignore imperfections in the market for fuel economy innovations, caused by spillovers; nearly all empirical studies suggest social returns to R&D substantially exceed private returns, due to incomplete appropriability (e.g., Mansfield et al. 1977, Hall 1995). To the extent tightening CAFE would spur new innovation, without crowding out R&D elsewhere in the economy, it may induce a significant source of welfare gain that is excluded from our calculations.

On the other hand, we ignore additional costs of CAFE due to its effect on compounding preexisting tax distortions in the economy-wide labor market; higher vehicle prices effectively lower the real value of household wages, and thereby reduce, slightly, aggregate labor supply. Based on formulas derived in Goulder et al. (1999) for an emission standard, we would project that fiscal interactions raise costs of complying with CAFE by around 20%.

Finally, we do not model the potential for CAFE to affect external accident costs through manufacturers reducing vehicle weight or size. However, the magnitude and direction of any resulting welfare effect is unclear as our results suggest fairly modest discrepancies in external accident costs across vehicles and a mixed relation between external costs and weight. This is broadly consistent with an econometric assessment by Noland (2004), which finds little relation between average fleet fuel economy and highway fatalities in recent years.

References

- Anderson, Soren, and Richard Newell, 2004. "Prospects for Carbon Capture and Storage Technologies." *Annual Review of Environment and Resources* 29: 109-142.
- CBO, 2003. *The Economic Costs of Fuel Economy Standards Versus a Gasoline Tax*. Congressional Budget Office, Washington, DC.
- CBO, 2002. *Reducing Gasoline Consumption: Three Policy Options*. Congressional Budget Office, Washington, DC.
- CEC, 2003. *Benefits of Reducing Demand for Gasoline and Diesel*. California Energy Commission, Sacramento, CA.
- Crandall, Robert W., and John G. Graham, 1989. "The Effects of Fuel Economy Standards on Automobile Safety." *Journal of Law and Economics* 32: 97-118.
- Davidson, Russell, and James G. MacKinnon, 1981. "Several Tests for Model Specification in the Presence of Alternative Hypotheses." *Econometrica* 49: 781-93.
- DOC, 2000. *Statistical Abstract of the United States*. Department of Commerce, Washington, DC.
- Dreyfus, Mark K., and W. Kip Viscusi, 1995. "Rates of Time Preference and Consumer Valuations of Automobile Safety and Fuel Efficiency." *Journal of Law and Economics* 38: 79-98.
- EIA, 2002. *Annual Energy Review 2001*. Energy Information Administration, U.S. Department of Energy, Washington, DC.
- EPA, 1999. "Development of Light-Duty Emission Inventory Estimates in the Notice of Proposed Rulemaking for Tier 2 and Sulfur Standards." EPA-420-R-99-005, Office of Air and Radiation, Washington, DC.
- FHWA, 1997. *Highway Cost Allocation Study 1997*. Federal Highway Administration, Department of Transportation, Washington DC.
- Frederick, Shane, George Loewenstein, and Ted O'Donoghue, 2002. "Time Discounting and Time Preferences: A Critical Review." *Journal of Economic Literature* 40: 351-401.
- Gerard, David, and Lester Lave, 2003. "The Economics of CAFE Reconsidered: A Response to CAFE Critics and a Case for Fuel Economy Standards." AEI-Brookings Joint Center for Regulatory Studies, Regulatory Analysis 03-01.

- Goldberg, Pinelopi Koujianou, 1998. "The Effects of the Corporate Average Fuel Efficiency Standards in the US." *Journal of Industrial Economics* 46:1-33.
- Goulder, Lawrence H., Ian W.H. Parry, Robertson C. Williams, and Dallas Burtraw, 1999. "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting." *Journal of Public Economics* 72: 329-360, 1999.
- Greene, David L. 1991a. "Short-run Pricing Strategies to Increase Corporate Average Fuel Economy." *Economic Inquiry* 29 pp. 101-114.
- , 1991b. "A Note on OPEC Market Power and Oil Prices." *Energy Economics* 123-129.
- Greene, David L., and Janet L. Hopson, 2003. "An Analysis of Alternative Forms of Automotive Fuel Economy Standards for the United States." Paper presented at the 2003 Transportation Research Board Annual Meetings.
- Greene, David L., James R. Kahn, and Robert C. Gibson, 1999. "Fuel Economy Rebound Effect for Household Vehicles." *The Energy Journal* 20:1-31.
- Greene, David, L., Philip D. Patterson, Margaret Singh, and Jia Li, 2004. "Feebates, Rebate and Gas-Guzzler Taxes: A Study of Incentives for Increased Fuel Economy." *Energy Policy*, forthcoming.
- Hall, Bronwyn, 1995. "The Private and Social Returns to Research and Development." In B. Smith and C. Barfield (eds.), *Technology, R&D, and the Economy*, Brookings Institution, Washington, DC.
- Harrington, Winston, 1997. "Fuel Economy and Motor Vehicle Emissions." *Journal of Environmental Economics and Management* 33.
- Harrington, Winston, James Sanchirico, and Margaret Walls, 2003. "Effects of Climate Change Policies on the U.S. Household Transportation Sector." Working paper, Resources for the Future, Washington, DC.
- Kahane, C.J., 1997. *Relationships Between Vehicle Size and Fatality Risk in Model Year 1985-93 Passenger Cars and Light Trucks*. DOT HS 808 570, National Highway Traffic Safety Administration, Washington, DC.
- Khazzoom, J. Daniel, 1997. "Impact of Pay-at-the-Pump on Safety Through Enhanced Vehicle Fuel Efficiency." *The Energy Journal* 18:103-133.
- Kleit, Andrew N., 2004. "Impacts of Long-Range Increases in the Corporate Average Fuel Economy (CAFE) Standard." *Economic Inquiry* 42: 279-294.

- Kleit, Andrew N., and Randall Lutter, 2004. "Increasing CAFE Standards: Still a Very Bad Idea." AEI-Brookings Joint Center for Regulatory Studies, Regulatory Analysis 04-04.
- Leiby, Paul N., Donald W. Jones, T. Randall Curlee, and Russell Lee, 1997. *Oil Imports: An Assessment of Benefits and Costs*. Oak Ridge, Tennessee: Oak Ridge National Laboratory.
- Leiby, Paul N., and Jonathan Rubin, 2001. "Effectiveness and Efficiency of Policies to Promote Alternative Fuel Vehicles." *Transportation Research Record* 1750: 84-91.
- Lutter, Randall, and Tro Kravitz, 2003. "Do Regulations Requiring Light Trucks to be More Fuel Efficient Make Economic Sense?" An Evaluation of NHTSA's Proposed Standards." AEI-Brookings Joint Center for Regulatory Studies, working paper 03-2.
- Mansfield, Edwin, John Rappaport, Anthony Romeo, Samuel Wagner, and George Beardsley, 1977. "Social and Private rates of Return from Industrial Innovations." *Quarterly Journal of Economics* 16: 221-240.
- McCarthy, Patrick S., 1996. "Market Price and Income Elasticities of New Vehicle Demands." *Review of Economics and Statistics* 78: 543-547.
- Miller, Ted R., David T. Levy, Rebecca S. Spicer, and Diane C. Letina, 1998. "Allocating the Costs of Motor Vehicle Crashes Between Vehicle Types." *Transportation Research Record* 1635: 81-87.
- NCEP, 2004. *Ending the Energy Stalemate: A Bipartisan Strategy to Meet America's Energy Challenges*. National Commission on Energy Policy, Washington, DC.
- NHTSA, 2002a. *Corporate Average Fuel Economy Standards for MY 2005-2007 Light Trucks*. National Highway Traffic Safety Administration, Washington, DC: US Department of Transportation.
- , 2002b. *The Economic Impact of Motor Vehicle Crashes 2000*. National Highway Traffic Safety Administration, US Department of Transportation, Washington, DC.
- , 1994. *Traffic Safety Facts 1993*. National Highway Traffic Safety Administration, Washington, DC: Department of Transportation.
- Noland, Robert B., 2004. "Motor Vehicle Fuel Efficiency and Traffic Fatalities." *The Energy Journal* 25: 1-22.
- NRC, 2002. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*. National Research Council, Washington, DC, National Academy Press.

- , 1992. *Automotive Fuel Economy: How Far Should we Go?* National Research Council, Washington, DC, National Academy Press.
- Orazio, Attanasio, Pinelopi K. Goldberg, and Ekaterini Kyriazidou, 2000. “Credit Constraints in the market for Consumer Durables: Evidence from Micro Data on Car Loans.” NBER working paper # 7694.
- , 2005 “Is Pay-as-You-Drive Insurance a Better Way to Reduce Gasoline than Gasoline Taxes?” Prepared for *American Economic Review, Papers and Proceedings*, forthcoming May 2005.
- Parry, Ian W.H., 2004. “Comparing Alternative Policies to Reduce Traffic Accidents.” *Journal of Urban Economics* 56: 346-368.
- Parry, Ian W.H., and Kenneth A. Small, 2004. “Does Britain or The United States Have the Right Gasoline Tax?” *American Economic Review*, forthcoming.
- Pearce, David, 2003. “The Social Cost of Carbon and its Policy Implications.” *Oxford Review of Economic Policy* 19: 362-384.
- Safirova, Elena, Kenneth Gillingham, Ian W.H. Parry, Peter Nelson, Winston Harrington, and David Mason “Welfare and Distributional Effects of HOT Lanes and other Road Pricing Policies in Metropolitan Washington DC, 2004” In Georgina Santos (ed.), *Road Pricing: Theory and Practice, Research in Transportation Economics* 9, Elsevier: 179-206.
- Schneider, Stephen H., 2004. “Abrupt NonLinear Climate Change, Irreversibility, and Surprise.” *Global Environmental Change* 14: 245-258.
- Schrank, D., and T. Lomax, 2002. *The 2002 Urban Mobility Report*. Texas Transportation Institute, Texas A&M University, College Station, TX.
- Shirley, Chad, and Clifford Winston, 2004. “Firm Inventory behavior and the Returns from Highway Infrastructure Investments.” *Journal of Urban Economics* 55: 398-415.
- Small, Kenneth A., and Camilla Kazimi, 1995. “On the Costs of Air Pollution from Motor Vehicles.” *Journal of Transport Economics and Policy* 29: 7-32.
- Small, Kenneth A., and Kurt van Dender, 2004. “The Effect of Improved Fuel Economy on Vehicle Miles Traveled and on Carbon Dioxide Emissions: Estimating the Rebound Effect Using US State Data, 1966-2001.” Working paper, Department of Economics, University of California, Irvine.
- Thorpe, Steven G., 1997. “Fuel Economy Standards, New Vehicle Sales, and Average Fuel Efficiency.” *Journal of Regulatory Economics* 11:311-326.

- Tol, Richard S.J., 1999. "The Marginal Costs of Greenhouse Gas Emissions." *The Energy Journal* 20:61-82.
- Tol, Richard S.J., Samuel Fankhauser, Richard Richels, and J. Smith, 2000. "How Much Damage Will Climate Change Do? Recent Estimates." *World Economics* 1:179-206.
- van Auken, R.M., and J.W. Zellner, 2002. *An Assessment of the Effects of Vehicle Weight on Fatality Risk in Model Year 1985-98 Passenger Cars and 1985-97 Trucks*. Dynamic Research Inc., Torrance, CA.
- Yang, H., and H.J. Huang, 1998. "Principle of Marginal Cost Pricing: How Does it Work in a General Road Network?" *Transportation Research A* 32: 45-54.
- Yee, J., 1991. "Effect of Consumption Standards on US Gasoline Consumption." *Journal of Policy Modeling* 13: 205-227.

Appendix A: Analytical Derivations

Deriving Equation (15)

Using (1), (4)-(9), and assuming binding regulation $g = \bar{g}$, the representative agent's indirect utility function, $V(\cdot)$, where fuel costs are correctly estimated, is defined by:

$$(A1) \quad V(\pi, \bar{g}, F, H, a_{EXT}, O, Z_M, Z_G) = \text{MAX} \quad u(D(v, m, H), \pi M, q(g^{R1} - \bar{g})M, X) \\ - a_{INT} - a_{EXT} - O - Z_M - Z_G \\ + \lambda \{I + F - X - v(p^{R1} + C(g^{R1} - \bar{g}) + p_G m \bar{g})\}$$

Partially differentiating (A1) gives:

$$(A2) \quad V_\pi = u_T M, \quad V_{\bar{g}} = \{\omega' q' u_X + \lambda v(C' - p_G m)\} v, \quad V_F = \lambda, \quad V_H = u_H, \\ V_{a_{EXT}} = V_O = V_{Z_M} = V_{Z_G} = -1$$

where we have used $\omega' u_X = u_Q m$. Totally differentiating the indirect utility function in (A1) with respect to \bar{g} , using (5)-(7) and (10) gives:

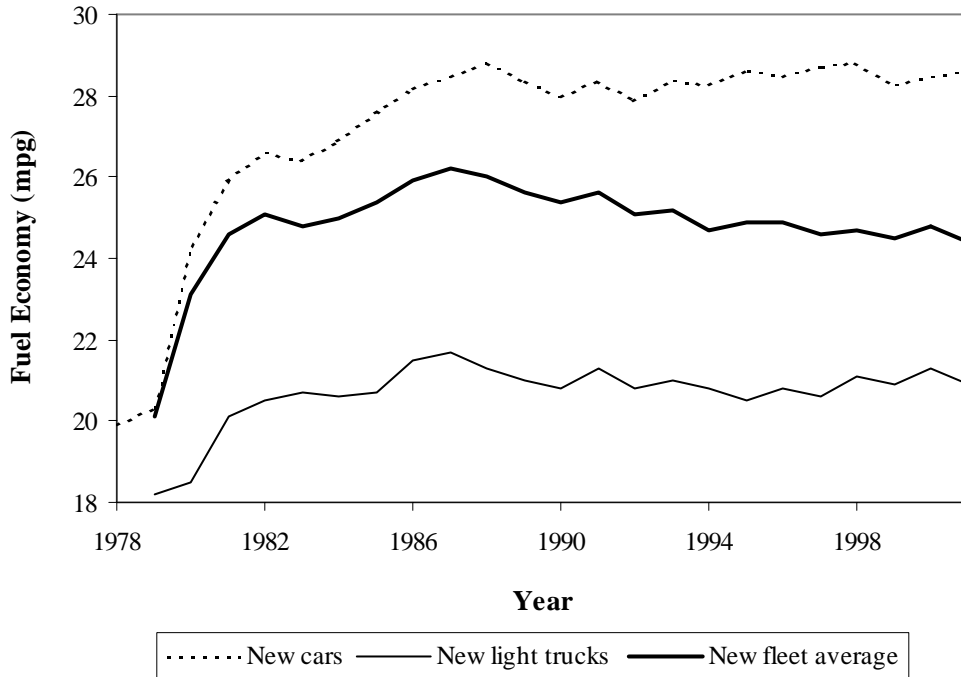
$$(A3) \quad \frac{dV}{d\bar{g}} = \left\{ V_{Z_G} Z'_G + V_O O' + \left(V_F \frac{dF}{d(t_G G)} + V_H \frac{dH}{d(t_G G)} \right) t_G \right\} \frac{dG}{d\bar{g}} \\ + \{V_\pi \pi' + V_{a_{EXT}} a'_{EXT} + V_{Z_M} Z'_M\} \frac{dM}{d\bar{g}} + V_{\bar{g}}$$

Equation (15) can be obtained from substituting (A2) into (A3), dividing by $\lambda = u_X$ to convert to money units, and using (15b).

Equation (15c) follows from (1c), (2), (12a), and (12b).

Tables and Figures

Figure 1. Fuel Economy Averages for Model Years 1978-2001



Source: NHTSA (2002a).

Figure 2. Equilibrium in the Second Reference Scenario

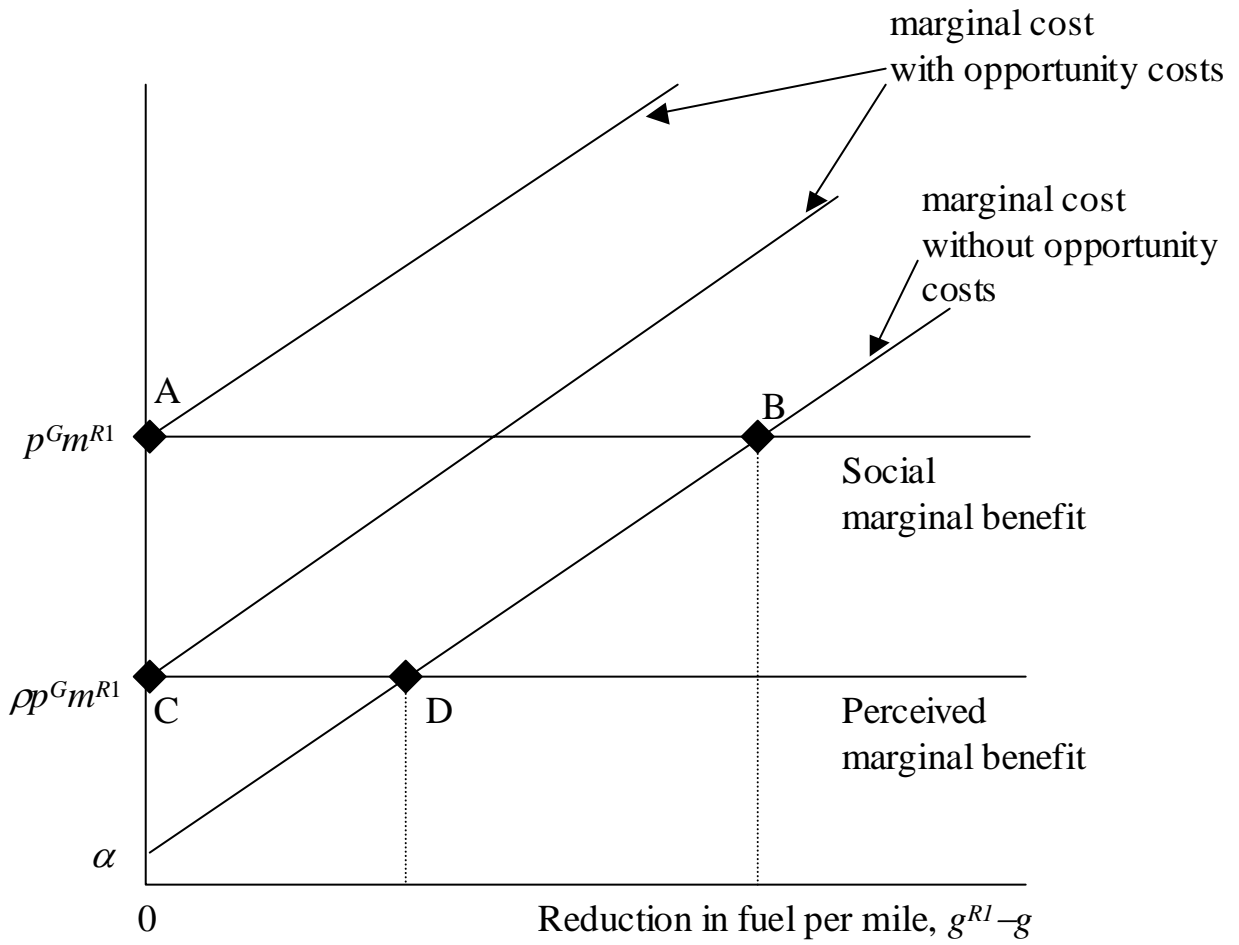


Figure 3. Fuel Economy and Emission Deterioration Rates

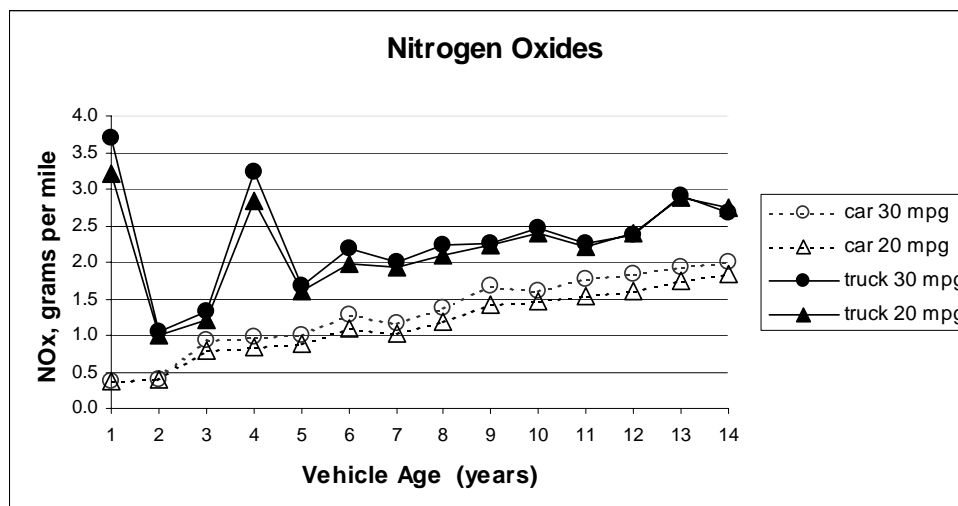
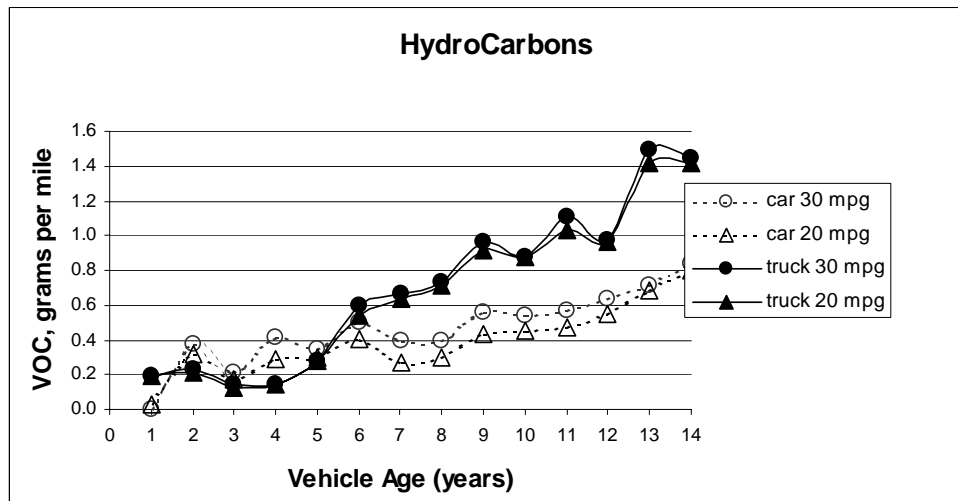
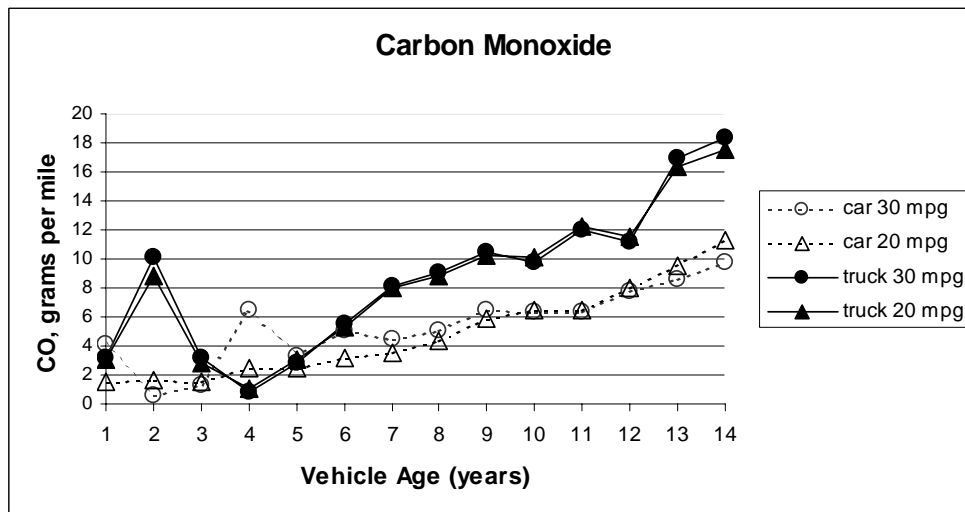


Figure 4. Sensitivity of Single-Vehicle Results

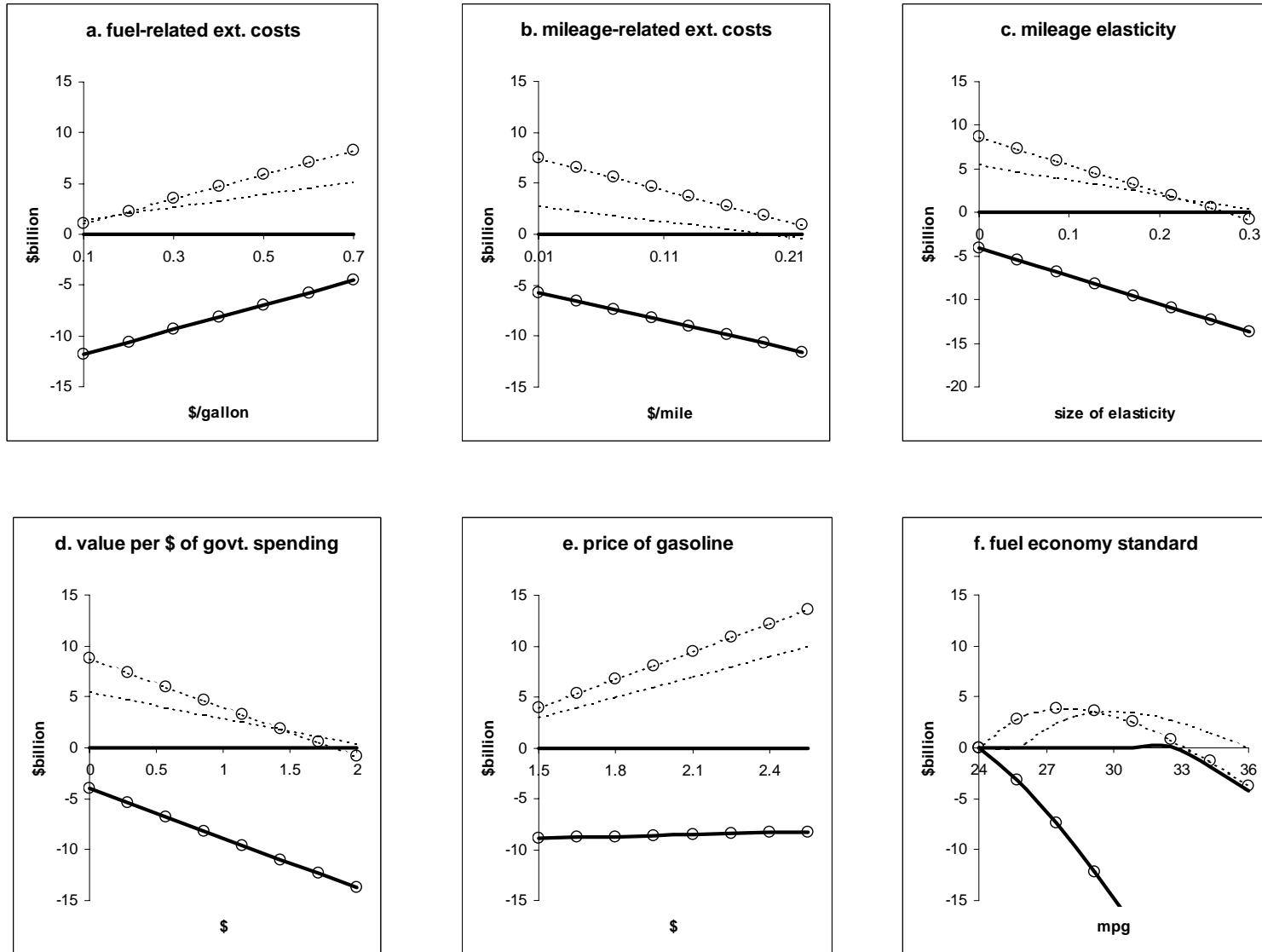


Table 1. Year 2000 Vehicle Data
(Representing the First Reference Scenario)

Vehicle class	Sales (thousands)	Initial price, \$	Initial certified fuel economy		Actual lifetime fuel costs, \$	fuel economy cost parameters	
			mpg	gal/100 miles		α^i	β^i
cars							
subcompact	756	15,280	30.2	3.3	7,558	368	2892
compact	2,650	15,647	29.1	3.4	7,844	310	2789
midsize	3,205	21,907	26.2	3.8	8,712	81	2638
large	748	25,266	23.9	4.2	9,550	641	1569
total cars	7,359	19,314	27.4	3.6	8,324	250	2610
light trucks							
small SUV	617	18,571	23.3	4.3	9,796	336	1559
mid SUV	1,672	27,557	20.3	4.9	11,244	85	1390
large SUV	834	34,051	16.6	6.0	13,750	174	818
small pickup	1,026	17,551	22.2	4.5	10,282	102	1705
large pickup	2,121	23,362	22.4	4.5	10,190	201	936
minivan	1,200	24,490	17.9	5.6	12,751	243	1563
total trucks	7,470	24,481	20.6	4.9	11,077	176	1282
total cars and truck	14,829	21,917	24.0	4.2	9,515	213	1941

Sources: NRC (2002) and authors' own calculations based on *Wards Automotive Handbook 2001* and *Edmunds.com*.

Table 2. Vehicle Demand Elasticities

	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: Own estimation using GM and Harrington et al. (2003) models.

Table 3. External 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											
Ped. & cycl. deaths	0.80	0.60	0.42	0.66	0.40	0.42	0.30	0.70	0.72	0.40	0.56
Ped. & cycl. injuries	0.40	0.25	0.19	0.24	0.14	0.30	0.07	0.17	0.16	0.13	0.21
Other vehicle deaths											
Other vehicle injuries	0.71	0.68	0.55	0.84	0.74	0.90	0.53	1.15	1.71	0.56	0.81
Property damage	1.23	0.98	0.71	0.94	0.60	0.88	0.42	0.98	0.96	0.56	0.84
Traffic holdups	0.51	0.39	0.26	0.30	0.20	0.26	0.13	0.31	0.24	0.20	0.29
Other economic costs	0.29	0.22	0.15	0.17	0.11	0.15	0.07	0.17	0.14	0.12	0.17
med., em. serv., legal, etc.	1.85	1.36	0.89	1.06	0.78	0.84	0.47	1.28	1.01	0.67	1.07
wages/household prod.	0.67	0.52	0.38	0.49	0.31	0.47	0.21	0.49	0.47	0.29	0.44
Total (cents/mile)											
Unadjusted	6.46	5.00	3.56	4.71	3.27	4.23	2.21	5.25	5.41	2.93	4.39
Adjusted for driver age	5.63	4.46	3.57	5.00	3.49	4.86	2.49	5.33	5.74	3.35	4.39

Source: Own estimates compiled using crash data from the Fatality Analysis Reporting System and the General Estimates System; injury cost valuations from NHTSA (2002b); and mileage data from the National Personal Transportation Survey.

Table 4. Benchmarks Results for Single-Vehicle Model
(effect of 4 mpg increase in fuel economy standard)

	Far-sighted consumers		Myopic consumers	
	No opp. costs	opp. costs	No opp. costs	opp. costs
Certified fuel economy in second reference scenario				
gallons per 100 miles	3.2	4.2	3.9	4.2
miles per gallon	30.8	24.0	25.7	24.0
Change in gasoline from second ref. scenario				
billion gallons (discounted)	0	-12.1	-6.3	-12.0
%	0	-13.0	-6.8	-12.9
Change in vehicle miles				
billion (discounted)	0	27.7	20.4	31.6
%	0	1.5	1.1	1.7
Change in vehicle sales				
thousand	0	-127.6	-32.1	-97.7
%	0	-0.9	-0.2	-0.7
Components of welfare change, \$billion (discounted)				
total	0	-8.89	2.96	3.95
gasoline reduction	0	-0.74	-0.38	-0.73
mileage increase	0	-3.43	-2.53	-3.92
fuel economy	0	-4.72	5.88	8.60
production cost	0	-6.12	-4.88	-6.85
opportunity cost	0	-18.11	0	-4.66
fuel savings	0	19.51	10.76	20.11
Welfare change per gallon of fuel reduction, \$	0	-0.73	0.47	0.33

Table 5. Results from the Multi-Vehicle Model
(effect of 4 mpg increase in fuel economy standard)

	Far-sighted consumers		Myopic consumers	
	No opp. costs	opp. costs	No opp. costs	opp. costs
Change in certified miles per gallon				
subcompact	0	4.2	2.7	4.2
compact	0	4.0	2.6	4.0
midsize	0	3.6	2.4	3.6
large	0	5.2	3.1	5.2
small SUV	0	3.9	2.6	3.9
mid SUV	0	3.6	2.4	3.6
large SUV	0	4.4	3.0	4.4
small pickup	0	3.4	2.3	3.5
large pickup	0	4.3	2.9	4.3
minivan	0	3.6	2.4	3.6
all cars and trucks	0	4.1	2.7	4.1
Change in vehicle sales price, \$				
subcompact	0	-77	-98	-77
compact	0	66	-26	66
midsize	0	414	174	414
large	0	727	486	727
small SUV	0	-114	-138	-115
mid SUV	0	272	96	272
large SUV	0	1,004	503	1005
small pickup	0	-54	-95	-55
large pickup	0	736	351	737
minivan	0	26	-49	261
all cars and trucks	0	270	88	290
Change in vehicle sales, %				
subcompact	0	2.02	1.25	1.94
compact	0	-0.15	0.56	0.15
midsize	0	-1.56	-0.87	-1.82
large	0	-3.26	-2.36	-2.16
small SUV	0	3.30	2.07	2.11
mid SUV	0	1.17	-0.02	-0.10
large SUV	0	-2.64	-1.48	-2.36
small pickup	0	4.58	1.70	2.01
large pickup	0	-3.13	-1.83	-3.47
minivan	0	1.51	0.75	0.56
all cars and trucks	0	-0.30	-0.22	-0.74
Change in gasoline, billion gallons (discounted)	0	-10.6	-6.6	-10.8
Components of welfare change, \$billion (discounted)				
total	0	-12.00	1.44	1.14
gasoline reduction	0	-0.65	-0.40	-0.66
mileage increase	0	-4.98	-3.07	-3.78
fuel economy	0	-6.37	4.91	5.58
production cost	0	-8.45	-6.36	-8.35
opportunity cost	0	-15.99	0.00	-3.90
social value of fuel savings	0	18.06	11.27	17.82
Welfare change per gallon of fuel reduction, \$	0	-1.13	0.22	0.11

Table 6. Raising Light-Truck Standard to Car Standard

	Far-sighted consumers		Myopic consumers	
	No opp. costs	opp. costs	No opp. costs	opp. costs
Without trading of fuel economy credits across cars and trucks				
Change in gasoline, billion gallons (discounted)	0	-11.57	-4.26	-11.21
Components of welfare change, \$million (discounted)				
total	0	-9.43	1.27	1.27
gasoline reduction	0	-0.71	-0.26	-0.68
mileage increase	0	-0.51	-1.70	-1.15
fuel economy	0	-8.21	3.23	3.10
production cost	0	-10.06	-3.94	-9.96
opportunity cost	0	-15.38	0.00	-3.99
fuel savings	0	17.23	7.17	17.05
Welfare change per gallon of fuel reduction, \$	0	-0.82	0.30	0.11
With trading				
Change in gasoline, billion gallons (discounted)	0	-11.14	-6.55	-10.87
Components of welfare change, \$million (discounted)				
total	0	-7.85	2.47	2.83
gasoline reduction	0	-0.68	-0.40	-0.66
mileage increase	0	-1.41	-1.82	-1.95
fuel economy	0	-5.76	4.69	5.45
production cost	0	-7.67	-5.78	-7.65
opportunity cost	0	-14.97	0.00	-3.71
fuel savings	0	16.88	10.47	16.81
Welfare change per gallon of fuel reduction, \$	0	-0.70	0.38	0.26