Preliminary Draft

An Equilibrium Model for Analyzing Automobile Fuel-Use and Pollution Policies

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1. Introduction

The automobile is an important part of the life of most Americans. The ratio of privately owned or leased automobiles to households in the U.S. is currently 2.0, and the average adult American drives 27.4 miles daily and spends over one hour on the road.

The use of the automobile raises important public policy issues. These include national security: gasoline use is the major source of demand for crude oil, and the increased demand for imports of crude oil raises concerns about vulnerability to foreign supply disruptions. The automobile is also a principal source of air pollution. In the U.S., automobiles account for approximately 60 percent of local carbon monoxide concentrations, 20 percent of local nitrogen oxide concentrations, and 5.7 percent of the emissions of carbon dioxide, the principal "greenhouse gas" contributing to global climate change.

The Federal government currently regulates automobile use, emissions, and fuel consumption through several channels. Since the passage of the Motor Vehicle Pollution Control Act in 1965, the U.S. has set limits on emissions concentrations of various hydrocarbons emanating from the tailpipes of U.S.-owned cars. In addition, it has imposed fuel economy standards on passenger cars and "light trucks." The increasingly popular sport-utility vehicles fall in the latter category. The Federal government also requires the installation of pollution-control equipment (including catalytic converters) in internal-combustion-engine automobiles.

Recently many analysts have called for new or more stringent policies to discourage gasoline consumption or reduce pollution emissions from automobiles. In a recent report, the National Research Council recommended increases in corporate average fuel economy (CAFE) standards on both passenger cars and light trucks (NRC, 2002). The Cato Institute has endorsed an increase in the Federal gasoline tax. A recent study by the Congressional Budget Office (2002) finds that a gasoline tax increase would be a highly cost-effective option, but indicates as well that the combination of a gasoline tax increase and a tightening of CAFE Standard could be worthwhile. Several analysts have favored broad measures to encourage individuals or firms to scrap their old (and especially high-polluting) vehicles, although several environmental groups have opposed such policies, particularly if they are accompanied by provisions enabling firms to credit the scrapping of vehicles against their obligations to reduce emissions from other (stationary) pollution sources.

In the past decade, researchers have made considerable strides in developing methods for evaluating automobile-related policies. However, existing studies suffer some significant limitations. One is the lack of integrated treatment of the markets for new cars, used cars, scrapped vehicles and public transportation. Studies by Berry, Levinsohn, and Pakes (1995) and by Goldberg (1995) consider only the supply and demand for new vehicles. Yet automobile policies can influence gasoline use, pollution, and individual welfare not only by affecting the new car market but by influencing the used car market as well. This is the case even if the policy (as with a CAFE standard) is targeted to newly produced automobiles. Moreover, the impacts of automobile policies depend importantly on how the composition of the automobile market changes through time. One important dynamic – affecting individual welfare as well as aggregate pollution and gasoline demand – is the gradual penetration of regulated vehicles (for example, newly produced cars) into the car market as the new cars age and replace older vehicles. This dynamic is analogous to the gradual replacement of the capital stock by new capital following a policy oriented toward new capital. Analyzing these effects requires attention to the changing age-composition of the automobile fleet.

A second limitation is the lack of close attention to household heterogeneity. Households differ in their existing car endowments and in their tastes for automobiles. Attention to such heterogeneity is crucial to assessing impacts on household welfare and the distribution of these impacts across households.

Third, most existing studies focus on just one policy instrument – a change in gasoline taxes, a tightening of CAFE standards, or a subsidy to retirement of old cars. This reflects the fact that studies usually are tailored to one instrument and capture only a subset of the major channels through which policies have their economic impacts. The lack of a comprehensive framework makes it difficult to compare alternative policy options.

This paper develops an analytical framework for assessing the distributional impacts of three automobile-oriented policies: an increase in the federal tax on gasoline, a tightening of CAFE standards, and a subsidy to retirements of old vehicles. The model incorporates interactions between the new and used car markets, takes account of household heterogeneity, and encompasses most of the important channels through which all three policies yield behavioral adjustments and welfare impacts. The model indicates how a policy's welfare impacts depend on the household's income, its taste for car attributes, and its initial vehicle endowment. In calculating households' welfare impacts, we consider only the private costs or benefits, disregarding the welfare effects from changes in pollution or from other externalities (such as reduced vulnerability to disruptions in the world oil market) associated with lower gasoline use.

We also perform policy simulations with a numerical model that closely resembles the numerical model. While the analytical model displays welfare impacts for individual households, the numerical model draws from a large sample of households to yield statistics on economy-wide impacts. By aggregating the impacts across households, the numerical model can calculate economy-wide costs, enabling us to compare the cost-effectiveness of the different policies in yielding given targets for reducing either gasoline consumption or automobile-generated pollution.

The results from these numerical simulations are meant to be qualitative. In a parallel project, we are developing a more detailed, econometrically estimated simulation model that will offer serious quantitative assessments. This extended model will allow for additional dimensions of household heterogeneity and, in contrast with the current model, deal with the imperfectly competitive nature of the automobile industry.

A main analytical contribution is to show how the welfare costs to individuals stem from the ease or difficulty of adjustments on both the car-purchase and the intensity-of-use (vehicle-miles-traveled) margins. The discreteness of car types is relevant to the cost of adjustments on the car-purchase margin. Because automobiles are discrete products, some individuals are closer to indifferent among automobile types than others. For a household that initially was close to indifferent between its current car and another car, the other car is effectively a close substitute. The analytical model shows that households enjoying such close substitutes will often suffer smaller welfare costs than households that do not have such substitutes.

The results from our numerical model, though qualitative, are informative and in some cases surprising. We find considerable differences across the three types of policies in the pattern of distributional impacts. Under the policy of a gasoline tax, the distributional impact depends closely on how the revenues from the tax are recycled to the private sector. For the case where the revenues are returned proportional to income, our results mirror Poterba's (1992) finding that the gasoline tax is regressive. However, if the revenues from the gasoline tax are instead returned lump-sum fashion (and equal to all individuals), then the burden of the policy falls more in the higher brackets of income and more so on individuals with preferences for larger vehicles.[1] The welfare impacts of the CAFE standard and retirement subsidy tend to be unevenly distributed across groups of households. The burden of the CAFE standard falls mainly on the agents who purchased new vehicles that did not meet the fuel-economy standard, while all other groups of households tend to gain from this policy. The retirement subsidy yields welfare gains to households with qualifying vehicles and who elect to accept the subsidy; nearly all other households experience welfare losses under this policy.

The relative cost-effectiveness of the different policies depends on whether the goal is reducing gasoline consumption or reducing automobile-generated pollution. For reducing gasoline consumption, the gasoline tax is the most cost-effective policy. The other policies have a narrower focus and invoke only a subset of the channels utilized by the gasoline tax. For reducing automobile-related pollution, the gasoline tax and retirement subsidy are far more cost-effective than the CAFE standard. Indeed, we find that tightening the CAFE standard leads to an *increase* in automobile related pollution by encouraging shifts to older, less fuel-efficient automobiles. This result attests to the importance of considering both the used-car and new-car markets in evaluating automobile policies.

The rest of the paper is organized as follows. Section 2 describes the analytical model and presents its results. Section 3 describes our simulation model and Section 4 presents this model's results. Section 5 concludes.

2. The Analytical Model

This section uses an analytical model to compare the costs of achieving reductions in gasoline use under alternative policy instruments. We lay out the main channels through which

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[1] Our finding, for gasoline taxes, parallels Metcalf's (1999) result that the distributional impacts of a composite "green" tax package depends significantly on how the revenues from this tax are recycled.

different automobile policies influence households, and show how different policies have different impacts through these channels. Here we focus on impacts at the individual level; we rely on the numerical model to reveal aggregate impacts and efficiency outcomes.

A. Household Behavior

Consider an economy with heterogeneous households. In this paper, we consider each household as a single decisionmaking unit. Each household enjoys utility from a consumption good (X) and from transportation services (T). Transportation services stem from the combination of vehicle (automobile) ownership (Q) and vehicle miles traveled (M). We write the utility function for individual *i* as:

$$(2.1)\quad U_i = u(X_i, \phi_i(q(S,A),M), \alpha_i)$$

where:

$$(2.2)\quad T = \phi(Q,M)$$

and

$$(2.3)\quad Q = q(S,A)$$

S and A denote respectively the size and age of the vehicle. For simplicity, we consider three ages of vehicles – new (N), old (O_1) and very old (O_2) – and two sizes – small (S) and large (L). We assume that every household owns exactly one vehicle. We also assume weak separability between X_i and ϕ_i. α_i is a scalar indicating household *i*'s tastes for the size of the vehicle. A higher value for α_i implies an increase in the relative utility from a large vehicle compared to a smaller one. To facilitate arriving at analytical results, we allow household tastes to be determined by two variables: income and the scalar α. A more detailed model might allow for additional taste parameters.

Households differ not only in their tastes but also in their money income and initial (beginning-of-period) vehicle endowment. Household i's "overall income" (y_i) is the sum of its money income $(\hat{y}_i)$ and the annuitized value of its vehicle endowment $(p_Q^0 Q^0)$, if any.

Each household maximizes its utility subject to a budget constraint of the form:

$$(2.4) \quad p_X X + p_Q Q + p_M = y$$

where we have suppressed the *i* subscript for convenience. p_X, p_M and p_Q represent the demand prices of X, M and Q, respectively. Note that Q and Q^0 need not be the same: an individual might sell her car endowment and purchase a different vehicle in the relevant time interval (one year). It is best to conceive of p_Q as the effective annual rental price of the services from vehicle Q. p_Q^0 is the price that when multiplied by Q^0 yields the annuitized value of the equity that the household has in its beginning-of-period vehicle endowment. It is convenient to think of the household as selling this endowment at the beginning of the period, and then electing whether to "buy back" that vehicle or purchase a different vehicle.

We assume that agents behave as price-takers and that transactions in the automobile market are costless.

The price of miles, p_M, can be expressed as:

$$(2.5) \quad p_M = \frac{p_G}{F(S,A)}$$

where p_G is the price of gasoline and F denotes fuel economy. We assume the following relationships between vehicle size or age and fuel economy:

$$(2.6) \quad F(L,j) < F(S,j) \qquad j = O_2, O_1, N;$$

and

$$(2.7) \quad F(i,O_2) < F(i,O_1) < F(i,N) \qquad i = S,L$$

These two assumptions enable us to identify the individuals that will select each type of automobile. For a given income Y, there exists a critical value for the automobile size parameter α for which an individual would be indifferent between a small and large car (of a given age). Let $\tilde{\alpha}$ denote that critical value. Note that $\tilde{\alpha}$ is an implicit function of Y. For example, among the individuals choosing very old cars (*O₂*), $\tilde{\alpha}$ satisfies:

(2.8) $V(p_{O_2}^{S}, p_X, p_G, Y_i, p_Q^0, \alpha(Y_i)) = V(p_{O_2}^{L}, p_X, p_G, Y_i, p_Q^0, \alpha(Y_i))$

where V denotes the indirect utility function. The mass of individuals selecting a particular car is defined by income and the automobile-size parameter (α). For example, the mass that selects (O_2, S) -- that is, very old, small cars – is defined by:

(2.9) $\int_{\underline{\alpha}}^{\tilde{\alpha}(Y)} \int_{\underline{Y}}^{Y_1} f(\alpha, Y)\, d\alpha\, dY$

where V denotes the indirect utility function.

Figure 1 illustrates how agents sort in the space of vehicles. Along the horizontal axis we measure income while in the vertical axis we measure the intensity of preference for the size of the vehicle. Both income and the taste parameter are bounded from above and below.

B. Policy Impacts

We use the framework just developed to analyze, at the household level, the behavioral impacts and associated welfare costs of various policies. We provide and interpret key equations below. Complete derivations are provided in Appendix A.

B.1 Gasoline Tax

Consider a tax of t_G imposed on gasoline consumption, with revenues recycled to the private sector in a lump-sum matter. The household's gasoline tax payment, L, is $t_G G$. Assume that aggregate revenues from the gasoline tax are returned to households as lump-sum transfers. Let T represent the transfer for a given household. In general, this transfer will not be the same as the household's gasoline tax payment. Let γ represent the ratio of the transfer to the gasoline tax payment; that is:

$$(2.10)\quad \gamma = T/(t_G \frac{M}{F})$$

In the presence of the gasoline tax, the household's budget constraint is:

$$(2.11)\quad p_X X + p_Q + (p_G + t_G)(M/F) = Y + T$$

The welfare impact of an increase in the gasoline tax depends on whether the household continues to choose the same vehicle (that is, hold on to the same car) after the policy is introduced. For individuals who choose the same vehicle, the welfare impact is: (see Appendix A):

$$(2.12)\quad \frac{1}{\lambda}\frac{dV}{dt_G} = \underbrace{t_G\left[\frac{dM}{dt_G}\frac{1}{F}\right]}_{VMT} + \underbrace{\frac{M}{F}(\gamma-1)}_{INCOME}$$

where λ is the marginal utility of income. Thus the left-hand side of (2.12) is the welfare impact in income units. The first term on the right-hand side of equation (2.12) represents the *VMT effect*. This is the traditional Harberger triangle, which equals the reduction in miles driven multiplied by the increase in the price of gasoline. The second term represents the *income effect*. This reflects the difference between the lump-sum transfer received and the gasoline tax payment. This effect vanishes in the special case where γ equals one.

Consider now the set of individuals who change vehicles in response to the increase in the gasoline tax. For these individuals, the welfare cost of the policy is given by:

$$(2.13)\quad \frac{1}{\lambda}\frac{dV}{dt_G} = \underbrace{t_G\left[\frac{dM}{dt_G}\frac{1}{F}\right]}_{VMT} + \underbrace{\frac{M}{F}(\gamma-1)}_{Income} + \underbrace{\gamma t_G\frac{M}{F}\left[\frac{dF}{dt_G}\frac{1}{F}\right]}_{Fuel\ \ Efficiency} + \underbrace{\left[\frac{dp_Q^0}{dt_G} - \frac{dp}{dt_G}\right]}_{Endowment}$$

For this set of individuals, two additional effects apply. These are represented by the third and fourth terms in the expression above. The *fuel efficiency effect* (third term) is equal to the change in fuel efficiency due to the change in vehicle multiplied by the initial tax bill on gasoline. A gasoline tax can be expected to alter fuel efficiency in at least two ways. First, by raising operating costs per unit of fuel, increases the incentive to obtain higher fuel economy. To the extent that older and larger cars tend to be less fuel-efficient (see equations (2.6) and (2.7)), this suggests that the gasoline tax encourages substitution to newer and smaller vehicles. The *endowment effect* (fourth term) is the difference in changes of prices of the initial endowment and the purchased vehicle.

This decomposition yields the following implications for the impacts of a gasoline tax. First, note that the VMT effect applies to all vehicle-owning households, while the fuel-efficiency effect only influences those households that switch vehicles in response to the gasoline tax. For an incremental change to the gasoline tax, these households are the ones that were indifferent between two vehicles prior to the policy change. In addition, note that the distributional impacts of the gasoline tax depend both on whether individuals are induced to change vehicles and on the values of γ for various households. Through its choices on how to recycle the revenues from a gasoline tax, the government can influence the distribution of the tax's welfare impacts across households.

B.2 CAFE Standard

We model the CAFE standard as a constraint in the fuel efficiency of new, large vehicles. For these vehicles, the CAFE Standard is the requirement that fuel efficiency be equal or greater than some value $\bar{F}$.

The impacts of the CAFE standard depend on whether the constraint is binding for a given individual; that is, it depends on whether, in the absence of this policy, and individual would have purchased a new, large vehicle with fuel-efficiency below $\bar{F}$.

Consider first the set of individuals for whom this constraint is binding. As detailed in Appendix A, for these individuals the welfare cost of an incremental increase in the CAFE standard is:

$$(2.14)\quad \frac{1}{\lambda}\frac{dV}{d\bar{F}} = -\underbrace{\left[\frac{dp_Q}{d\bar{F}}\right]}_{CFE} - \underbrace{M\left[\frac{d\,{}^{p_G}\!/_{F}}{dF}\frac{dF}{d\bar{F}}\right]}_{REBOUND}$$

The first term on the right-hand side of (2.14) is the welfare impact from the policy-induced change in the price of the vehicle. We denote this effect as the additional cost of meeting the fuel efficiency standard. The CAFE standard also generates a *rebound effect*, which stems from the policy's impact on miles driven. By requiring higher fuel-economy, this policy lowers the per-mile cost of driving, which induces more driving. This has an offsetting impact on fuel consumption. This "rebound" impact on fuel consumption, times the gasoline tax, is a negative welfare impact represented by the second term on the right-hand side of (2.12).

For the set of individuals who were indifferent between (N,L) and (N,S),the welfare effect of a tightening of the standard is:

$$(2.15)\quad V(p_X, p_N^S, p_M, \bar{F}, \alpha) - V(p_X, p_N^L, p_M, \bar{F}, \alpha).$$

Similarly, for the set of individuals who were indifferent between (O_1,L) and (N,L), the welfare effect is:

$$(2.16)\quad V(p_X, p_{O_1}^L, p_M, \bar{F}, \alpha) - V(p_X, p_N^L, p_M, \bar{F}, \alpha)$$

Finally, for all individuals who did not buy (N,L), the welfare effect is given by:

$$(2.16)\quad \frac{1}{\lambda}\frac{dV}{d\bar{F}} = \underbrace{\left[\frac{dp_Q^0}{d\bar{F}} - \frac{dp_Q}{d\bar{F}}\right]}_{endowment}$$

This is an endowment effect similar to the one under the gasoline tax.

This decomposition suggests two important differences between the impacts of a gasoline tax and a CAFE standard. First, while the gasoline tax applies to all vehicles (by raising their operating costs), the CAFE standard focuses on new, large vehicles, raising their prices relative to other cars. This tends to shift demands from larger to smaller new vehicles, and to shift demands from newer cars to older cars. Thus, we might expect greater changes in the composition of the automobile fleet under the CAFE standard than the gasoline tax.[2]

A second difference between the two policies is in the impact on miles driven. The gasoline tax raises the per-mile cost of driving for all cars. In contrast, by compelling new, large cars to meet a more stringent fuel-efficiency requirement, the CAFE standard reduces the per-mile operating cost of these cars. This tends to induce more driving by owners of these vehicles. This partly offsets the effectiveness of the CAFE standard in reducing demand for gasoline.

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[2] The compositional changes are tempered by price effects. Since the supply of older (that is, used) cars is largely fixed, the increase in demand for older vehicles leads to increases in the prices of older cars. This brings demand into balance with the nearly fixed supply. We say "nearly" here, because the supply of older cars can be altered through changes in the rates at which such cars are scrapped, that is, removed from the used-car market. We will discuss the scrap market in more detail in connection with the numerical model and its results.

B.3 Subsidy to Retirement of Old Vehicles

Finally, consider a subsidy of s_R offered to individuals who retire old vehicles. The retirement subsidy is motivated by the fact that older cars are less fuel-efficient. Hence by hastening the retirements of older cars, the subsidy raises the overall fuel-economy of the active vehicle fleet.

We will assume here that this subsidy applies old vehicles. This is only to simplify the exposition: it has no importance to the form of the results. In our numerical simulations, we relax this assumption and allow the subsidy to apply to all old vehicles that are retired. Let Z be the total revenue generated to fund the subsidy and $\gamma_R Z$ be contribution of individual *i* to the subsidy. The impacts of the retirement subsidy depend on whether a given household initially holds a qualifying old vehicle. For a household endowed with a qualifying vehicle, the budget constraint is

$$(2.17)\quad p_X - p_Q - \frac{p_G}{F} M = Y - \gamma_R Z + s_R$$

if the household retires the vehicle. If the household does not retire the vehicle, then it does not obtain the subsidy sR. Thus, the retirement subsidy introduces an opportunity cost for holding a qualifying vehicle. If the household retires the qualifying vehicle, the welfare cost of an incremental increase in the retirement subsidy is (see Appendix A):

$$(2.18)\quad \frac{1}{\lambda}\frac{dV}{ds_R} = 1 - \gamma\frac{\partial Z}{\partial s_R}$$

This is the subsidy rate net of individual's *i* net of his contribution to the funding of the subsidy. In contrast, if the household does not retire the qualifying vehicle (thus foregoing the subsidy), the welfare cost is:

$$(2.19)\quad \frac{1}{\lambda}\frac{dV}{ds_R} = -\gamma\frac{\partial Z}{\partial s_R} + \frac{dp_Q^0}{ds_R}$$

Individuals in this category pay the contribution to the funding of the subsidy. In addition, to the extent that the subsidy changes the value of their vehicle endowment, there is an additional welfare impact. This is given by the second right-hand term in (2.19).

For individuals that do not initially own qualifying vehicles, the cost of the subsidy is given by:

$$(2.20)\quad \frac{1}{\lambda}\frac{dV}{ds_R} = -\gamma\frac{\partial Z}{\partial s_R} + \left[\frac{dp_Q^0}{ds_R} - \frac{dp_Q}{ds_R}\right]$$

For these individuals, the welfare impacts depend on two elements. First, they depend on the contribution the individual must make to finance the subsidy. This is captured by the first right-hand-side term in (2.20). In addition, they depend on policy-induced changes in the prices of the individual's endowment and the car that the individual purchases. This is expressed by the second right-hand-side term.

The retirement subsidy differs from both the gasoline tax and the CAFE Standard in several ways. First, the subsidy shifts wealth toward people who own qualifying vehicles. The government can alter this redistribution through the distribution across households of the financing parameter γ_R .

Second, the retirement subsidy produces a different sort of composition effect from the other policies. While the CAFE standard tends to reduce the share of the vehicle fleet represented by new cars, the retirement subsidy tends to increase this share. To the extent that newer cars are more fuel-efficient, this composition effect of the retirement subsidy works toward reducing gasoline consumption.

Finally, we note that the subsidy to retirement of old vehicles fails to exploit the VMT effect. It has no direct impact on vehicle operating costs and thus has no direct effect on miles driven.

3. A Numerical Model

We incorporate the framework described above in a numerical model, which we employ to derive aggregate outcomes. The structure of this model matches that of the analytical model described in the previous section, except for a few extensions referred to below. The main difference from the analytical model is the use of specific functional forms.

A. Model Structure

1. Household Behavior

The indirect utility function for each household has the form:

$$(3.1) \qquad U_{i,j} = -\frac{1}{1+\eta_p}\left[\frac{p_M(j)}{p_X}\right]^{1+\eta_p} + e^c \frac{1}{1-\eta_Y}\left[\frac{Y_i - p_j}{p_X}\right]^{1-\eta_Y} + \alpha_{O1}O1_j + \alpha_{O2}O2_j + \alpha_{S_i}S_j$$

where U represents utility and p_M, p_X, $O1$, $O2$, and S are as defined in the previous section. The logit functional form is well-suited to the discrete choices the household makes among automobile types. η_P and η_Y the elasticities of vehicle miles traveled (VMT) with respect to price and income respectively.

To maximize utility, the household chooses whether to keep the car with which it is endowed, to sell it to the used car market and buy another new or used car, or to sell it to the scrap company and buy another new or used car.

Note that Y and α_S are indexed by household, while the price of miles (p_M), the rental price of the car (p), and the characteristics of the car are indexed by j, that is, type of car. The α's on age are common to all households and are chosen to approximate the age choices in the data. This form for indirect utility implies a demand for miles for each household where $j*$ is the utility maximizing choice of car from above:

$$(3.2) \qquad \ln(M_{i,j*}) = \eta_P \ln\left(\frac{p_M(j*)}{p_X}\right) + \eta_Y \ln\left(\frac{Y_i - p_{j*}}{p_X}\right) - c$$

Household demands are computed one household at a time. For each household, we evaluate $U_{i,j}$ for each car and identify the car that maximizes utility. The choice of vehicle miles traveled (M) is part of the utility-maximizing decision. This choice is connected to its choice of automobile type, since the household takes account of fuel-economy and the per-mile cost of driving in choosing the utility-maximizing automobile. By aggregating across households, we compute the total demand for each type of car, along with total vehicle miles traveled and aggregate gasoline consumption.

Note that household income used in this procedure is the sum of benchmark income, lump-sum transfer from the government, and the full change in rental price (relative to the benchmark) of the used car they are holding.

2. Prices and Market-Clearing in the Automobile Markets

In the model, the prices of X (the general consumption good) and of gasoline are exogenous. The fuel-efficiency of each type of car is also exogenous.

For new cars, producer prices are equal to exogenously specified marginal costs of production. New car quantities adjust to meet the demand for cars at the prices determined by marginal production costs. The assumption of marginal cost pricing is clearly unrealistic, but it simplifies the modeling considerably.[3] For used cars, market prices adjust to bring the demand for these cars into balance with supply.

For each type of used car, the supply is the "maximum potential supply" minus the number of cars that are scrapped during the period. For each type (age and size) of used car, the scrap price serves as a lower bound on the used car price. As indicated in Figure 2, these assumptions yield a "backwards-L" shaped supply curve for each used car type. The scrap price becomes a lower bound on the used car price. Let j index a given used car type, and let Z_j represent the aggregate endowment of vehicles of car type j. Let p_j represent the market price of used car j, and let p_{S_j} represent its scrap price. Figure 5-2 depicts two potential market equilibria. In first case, the demand curve is given by D^I and the demand for this type of used car exceeds Z_j at the scrap price p_{sj}. In this case, the market for this car type clears at a price $p_j^I > p_{S_j}$. The supply to households is Z_j, and no cars of this type are scrapped. In the second case, the demand curve for this type of used car is D^{II}, and demand falls short of Z_j at the scrap price p_{S_j}. In this case, the used car price is the scrap price. The supply to households is S_j^{II}, which meets household demand; the residual supply R_j is scrapped.

The three policies are modeled as follows. The gasoline tax is a per-unit tax that increases the price of gasoline. The CAFE policy is modeled as an increase in the marginal cost

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[3] In a parallel project, we are developing a more sophisticated numerical model that incorporates imperfect competition among producers of new cars.

of manufacturing large new cars, where markets again are assumed to clear at price equal to the new marginal cost. Each 1 percent increase in manufacturing cost improves fuel efficiency by 4 percent The retirement subsidy is a subsidy of 75 percent of the benchmark market value of very old and old large cars.

3. Government Budget Balance

In all simulations, any revenue generated or required by a policy is offset by lump-sum payments to or taxes imposed on households. The gasoline tax policy generates revenue and thus leads to a lump-sum payment; the retirement subsidy requires financing in the form of lump-sum taxes paid by households. The lump-sum transfers or taxes can either be constant across households or proportional to benchmark income.

4. Equilibrium

The model solves for equilibrium in the initial time period by new-car quantities, used-car prices, and lump-sum transfers or taxes such that: (1) for each type of new car, the aggregate supply equals its demand; (2) for each type of used car, either (a) the demand equals maximum potential supply at a price above the scrap price or (b) the demand is less than the maximum potential supply, the price equals the scrap price, and scrappage makes up the difference between the maximum potential supply and the demand; and (3) aggregate lump-sum transfers equal policy revenues generated. We apply a variant of Newton's method to obtain the equilibrium prices and quantities.

5. Dynamics

The numerical model solves for an equilibrium in the initial period; thus it yields the short run equilibrium. To get a glimpse of the long run, we assume that in successive periods the demands for new cars will match the demands in the first period. In addition, we update the stocks of older cars, allowing previously new cars to enter the O_1 category, and to allow some of the cars previously categorized as O_1 to enter the O_2 category. The extent of diffusion from one category to the next is based on the age-structure of each category in the benchmark. Under this approach, the fuel-economy of the overall automobile fleet gradually converges to the fuel-economy of the cars classified as new in the benchmark year (2002). A drawback of this approach is that it lacks an explicit treatment of intertemporal decisionmaking by households. At the same time, it has the virtue of simplicity, and the discrete choice formulation conforms well to empirical estimation.

B. Data and Calibration

To implement the model, we have combined information from the following data sources: The Consumer Expenditure Survey (CEX), the Ward's Automotive Yearbook, The National Automobile Dealers Association (NADA), The Kelly Blue Book (KBB), and the Oil Price Information Service (OPIS).

The household level data comes from the Consumer Expenditure Survey. It is representative of the US population for the year 2000. For the households who own vehicles, the survey reports the number of vehicles owned, the make, model and year of the vehicle, and the overall quarterly expenditure on gasoline and other operating costs items.

Vehicle miles traveled is inferred by taking the difference between odometer readings reported in consecutive quarters of the survey. The income distribution is truncated lognormal and fit to the distribution of income among car owners from the CEX data. The parameter α_S is distributed as a truncated normal. The distribution of α_S is calibrated so that the fraction of simulated households buying large cars approximates the data.

Price and income elasticities of demand for miles (η_P and η_Y) were set at -0.25 and 0.1 respectively for all households.

4. Numerical Results

This section presents our simulation results illustrating the impacts of gasoline taxes, fuel-efficiency standards, and subsidies to retirements of old vehicles. We consider the distribution of impacts across households as well as overall efficiency costs. We examine the efficiency costs of achieving given reductions in gasoline consumption, and in achieving given reductions in air pollution.

Table 1 presents the benchmark (or reference case) prices of cars, and the percentage of households who own different types of vehicles. Consistent with the CEX data, the share of new cars in the vehicle fleet is small (around 4 percent). The largest category is very old and small. Note that the prices are annualized prices. These vary between $768 and $4000.

4.1 Costs of Achieving Reductions in Gasoline Consumption

Figures 3a and 3b compare the economy-wide costs (measured by the equivalent variation) of reducing gasoline use under three policies. The two figures illustrate the costs for the short and long run respectively.

Short-Run Results

The blue line indicates total cost under the gasoline tax. This curve reflects the *VMT effect* described in equation (2.12). The positive and increasing slope reflects the increasing difficulty of substituting for driving, consistent with the *VMT effect* described in equation (2.12). The rising slope also is consistent with increasing difficulty of substituting to more fuel-efficient automobiles. Under low gasoline taxes, only the households that initially were close to indifferent between their original car and another car end up switching car types. Higher gasoline taxes cause additional households to switch. Such switching mitigates the costs to households from higher gasoline taxes, but it involves households moving to car types that they otherwise would not prefer.

The pink line shows the costs of achieving gasoline use reductions under the CAFE standard. The costs of achieving given reductions in gasoline consumption are considerably higher under this policy than under the gasoline tax. This reflects the fact the CAFE standard is a narrower policy than the gasoline tax: while the gasoline tax applies to all vehicles, the change in the CAFE standard only applies to new, large vehicles. In addition, the CAFE standard does not employ all of the margins for discouraging gasoline consumption that are invoked by the gasoline tax. The gasoline tax affects both the car-purchase decision and the car-use (or VMT) decision in ways that discourage consumption. By raising the per-mile cost of driving, the gasoline tax gives households incentives to purchase more fuel-efficient vehicles. In addition, it promotes lower miles traveled. In contrast, the CAFE standard only discourages consumption through the car-purchase margin – by inducing households to purchase more fuel-efficient vehicles. It does not promote lower VMT: indeed, because of the rebound effect, it can lead to higher VMT, which offsets the reduction in gasoline consumption directly attributable to improved fuel-economy. For these reasons, the CAFE standard is less cost-effective than the gasoline tax in reducing gasoline consumption.

The yellow line shows the costs under the subsidy to retirement of older vehicles. Achieving given reductions in gasoline use is also considerably more costly under this policy than under the gasoline tax. This is partly explained by the relatively narrow focus of the retirement subsidy: this subsidy targets only older vehicles while the gasoline tax applies to all cars. And the channels employed by the retirement subsidy are again more restricted than those under the gasoline tax. The retirement subsidy only directly affects the car-purchase decision – by reducing the supply, and thus raising the purchase price, of older cars. It does not directly affect the per-mile cost of driving, and thus it does not have any direct impact on VMT. It only influences VMT by enlarging the share of the active automobile fleet represented by newer, more fuel-efficient automobiles. Thus, the narrower focus of the retirement subsidy, as well as its focus only on the car-purchase margin, account for its higher costs in achieving given reductions in gasoline use.

Long-Run Results

In Figure 3b we compare the long-run costs of the different policies. The costs of all policies are lower in the long run than in the short run. This is in keeping with the fact that compositional changes can be more extensive in the longer run. Each of these policies raises demands for small new cars relative to the demand for larger (less fuel-efficient) new cars.

While the ratio of small to large cars is largely fixed for existing used cars (apart from changes due to scrappage), this ratio is variable for new cars. Over time, as older cars are retired, the ratio of small to large cars increases, as the preferences for smaller cars becomes more and more embodied in the overall car fleet. Thus, over time, the policies are able to affect fuel-economy more fully through changes in the size-composition of the automobile fleet. This accounts for the lower long-run policy costs.

The differences between short- and long-run costs are especially pronounced for the CAFE standard and retirement subsidy. In contrast with the gasoline tax, these two policies promote reductions in gasoline consumption almost exclusively by changing the composition of the vehicle fleet. As mentioned, such compositional changes are restricted in the shorter term because of the relatively fixed supply of older cars. However, over the long term, the changes can be more dramatic. Under the CAFE standard, the economy-wide improvements in fuel-economy are very limited in the short run, since the new standards only apply to vehicles that are new in the year the standard is first introduced. Only over time can the CAFE standard have a significant influence on fuel-economy, as the imposed fuel-economy improvements for new vehicles ultimately permeate the market for used vehicles, and once-new large cars (facing the standard) become older. Thus, the costs of achieving reductions in gasoline consumption under the CAFE standard are much lower in the longer run.

4.2 Costs of Achieving Reductions in Pollution

Figures 4a and 4b show the short- and long-run costs of achieving reductions in pollution under the three policy approaches. For the gasoline tax and retirement subsidy, the costs of achieving pollution reductions are lower in the long run than in the short run, for reasons paralleling those given above for gasoline consumption.

The results for the CAFE standard are particularly striking. The Clean Air Act imposes limits on ambient concentrations of carbon monoxide, nitrogen dioxide, and ozone (as well as other “criteria pollutants”). As part of their efforts to meet these limits, states impose tailpipe emissions standards on automobiles. These are imposed on an emissions-per-mile basis. If fuel economy improves, emissions-per-mile fall, other things equal. Suppose a state is currently just meeting its emissions-per-mile target, and then the CAFE standard is imposed. To the extent that fuel economy improves, emissions per mile will now fall below the requirement. Automobile manufactures could respond to this by allowing emissions per gallon of fuel to rise. The solid purple lines in Figure 4 assume that manufacturers make this adjustment. The dashed lines assume that they do not.

Note that in our simulations, both the solid and dashed lines for the CAFE standard are to the left of the vertical axis: this policy leads to *increases* in pollution according to our pollution index – even if automobile manufactures do not respond to the policy by allowing emissions per gallon to rise. The CAFE policy induces an increase in demand for older cars, which do not face the standard. This prompts a rise in the prices of these cars, and reduces the amount of scrappage. Thus the supply of old cars rises. These cars have higher pollution emissions per mile driven. In our simulations, the increased relative importance of older cars is sufficient to cause pollution to rise.

4.3 Composition of the Vehicle Fleet

Figures 5a-5d show the composition of the vehicle fleet under the benchmark (5a), gasoline tax (5b), CAFE standard (5c) and retirement subsidy (5d). The figure shows the changes in the short run. All policies were set to achieve a .5 percent reduction in gasoline use in the short run.

First, the gasoline tax (Figure 5b) creates incentives for a shift in the composition of the vehicle fleet toward newer and smaller vehicles. The horizontal boundary between individuals who prefer small vehicles and those preferring larger cars moves up. An individual who is indifferent between a small and large car is located on this boundary. Thus, to be indifferent between the two sizes of cars, a person must now have a greater taste for size.

Under the CAFE standard (Figure 5c), the fleet share of new large cars falls even more than under the gasoline tax. This reflects both a shift toward older cars (the left-hand boundary moves to the right) and a shift toward smaller new cars (the bottom boundary moves up). These shifts underlie the CAFE standard’s pollution consequences discussed above. By raising demands for older cars and causing an increase in their prices, this policy delays the retirement of older vehicles and exerts pressures toward increased pollution emissions.

The main impact of the retirement subsidy (Figure 5d) is a reduction in the relative size of very old, large vehicles: the copper-colored area in the top left portion is smaller than in the benchmark. The subsidy leads to cascading impacts on vehicle demands: the higher price of very old large cars causes an increase in demand for old (as opposed to very old) large cars, which in turn raises their prices and induces an increase in demand for large new cars. Thus, the purple area (corresponding to new large cars) is larger than in the benchmark.

4.4 Distribution of Impacts on Household Welfare

We now analyze the impacts of the three types of policies on the welfare of the various households. These impacts are displayed in figures 6a-6c. Households are defined by income and their tastes for automobile size. These two characteristics respectively correspond to the horizontal and vertical axes of the figures.

Figure 6a displays the impacts of the gasoline tax. For this policy, we consider two alternative methods of recycling the gasoline tax revenue. In the simulations for Figure 6a-1, all households receive the same lump-sum transfer. In the simulations for Figure 6a-2, the lump-sum transfers are proportional to each household's benchmark income.

In the case involving the constant transfer, households with a relatively high taste for large cars experience the largest welfare losses. These households are wedded to the cars whose operating costs rise the most under the gasoline tax. Most of the households with less of a taste for large size experience small welfare losses. Households with low income and little preference for large size enjoy a welfare gain. For these households, the lump-sum transfer is large relative to their gasoline tax payments. The gasoline tax payments are low these households tend to drive less and to drive (smaller) cars that are relatively fuel-efficient.

When gasoline tax revenues are recycled in proportion to income (Figure 6a-2), the distributional results are strikingly different. In this case, the principal determinant of the welfare impact is household income, rather than taste for size of vehicle. Apart from the recycling of revenues, the gasoline tax is a regressive policy: lower income households spend a considerably larger fraction of their incomes on gasoline than do higher income households. Under the previous policy involving a constant transfer, this regressive impact was offset by the progressivity of the transfer. Under income-proportional recycling, there is no such offset. For households with income lower than approximately 40,000 dollars, the policy translates into a welfare loss. The households who gain the most under this policy are the richer who own new cars. For these households the tax rebate more than compensates them for the tax payment.

The distributional impacts of the CAFE standard are represented in Figure 6b. The key difference between this figure and the figures for the gasoline tax is that the burden of the policy is concentrated on a much smaller group. Under the CAFE Standard, most households experience no change in welfare or even a small positive welfare gain due to the increase in the value of their endowment of used cars. The households that experience welfare loses are the ones that consumer large and new vehicles and had to support the costs of meeting the fuel economy standard.

Figure 6c displays the distributional impacts of the retirement subsidy. In our simulation, the subsidy is financed by a constant lump-sum tax paid by all households. In contrast with the CAFE standard, the burden of the retirement subsidy much more evenly spread throughout the population, in keeping with the fact that all households face the lump-sum tax to finance the subsidy. A relatively small fraction of households experience welfare gains. These are the households that are endowed with qualifying vehicles and that choose to retire their vehicles.

These distributional impacts give clues as to the political acceptability of different policy options. The proportion of households experiencing a welfare gain is largest under the CAFE standard. Thus, one might expect the CAFE standard to enjoy the most political support. This is broadly consistent with the politics of automobile policies in the U.S. over the past two decades.

5. Conclusions

We develop an analytical framework for examining the welfare impacts of three alternative automobile policies: an increase in gasoline taxes, a tightening of CAFE standards, and a subsidy to retirements of old (gas-guzzling) vehicles. The model aims to capture the heterogeneity of households' tastes for automobiles, the discreteness in automobile choices, and some important connections between the new car and used car markets. This framework is then incorporated in a numerical model that yields aggregate outcomes and compares the policies in terms of the aggregate costs of reducing gasoline consumption or automobile-generated pollution.

The analytical framework shows that the welfare costs to individuals stem from the ease or difficulty of adjustments on both the car-purchase and intensity-of-use (vehicle-miles-traveled) margins. The discreteness of automobile types implies that for some households, substitution options may be limited. This has a significant bearing on welfare impacts. As a related point, the form of the welfare impact differs depending on whether a policy induces a household to switch cars. The analytical framework illustrates these differences.

Although our numerical results are meant to be illustrative – more precise quantitative estimates require a more detailed numerical model – they nonetheless offer significant qualitative insights. In particular, the numerical experiments reveal significant differences between the short- and long-run impacts of the three policies. The differences are especially pronounced for the CAFE standard, whose effects unfold over time as newly regulated cars eventually penetrate the automobile fleet.

The relative cost-effectiveness of the different policies depends on whether the goal is reducing gasoline consumption or reducing automobile-generated pollution. For reducing gasoline consumption, the gasoline tax is the most cost-effective policy. The other policies have a narrower focus and invoke only a subset of the channels utilized by the gasoline tax. For reducing automobile-related pollution, the gasoline tax and retirement subsidy are far more cost-effective than the CAFE standard. Indeed, we find that tightening the CAFE standard leads to an *increase* in automobile related pollution by encouraging shifts to older, less fuel-efficient automobiles. This result attests to the importance of considering both the used-car and new-car markets in evaluating automobile policies.

The simulations suggest a trade-off between cost-effectiveness and political feasibility. While the gasoline tax is far more cost-effective than the CAFE standard for reducing gasoline consumption, the CAFE standard imposes welfare losses on a far smaller fraction of households. This is consistent with the greater political success of the CAFE policy.

Some shortcomings of this analysis deserve mention. Our framework assumes every household owns exactly one vehicle. In fact, over half of U.S. households own more than one vehicle (and some own none). Similarly, the range of transportation choices does not include the option of public transit. Also, our framework does not capture the intertemporal aspects of household decisionmaking, or the imperfectly competitive nature of the automobile industry. In related work we are aiming to address each of these issues.

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Appendix A

Deriving Equation (2.12)

The indirect utility function of an arbitrary individual is:

$V(p_X, p_Q, p_G, t_G, T, Y, \alpha)$ and is given by the solution to the problem

$$\underset{X,S,A,M}{Max}\ u(X, q(S,A), M, \alpha) + \lambda\left[Y + T - p_X X - p_Q - \left(\frac{p_G + t_G}{F}\right)M\right] \qquad \text{(A.1)}$$

Note that, by the envelope theorem:

$$\frac{\partial V}{\partial t_G} = -\lambda \frac{M}{F} \qquad \text{(A.2)}$$

$$\frac{\partial V}{\partial T} = \lambda \qquad \text{(A.3)}$$

$$\frac{\partial V}{\partial p_Q} = -\lambda \qquad \text{(A.4)}$$

The welfare effect of a marginal change in t_G is:

$$\frac{dV}{dt_G} = \frac{\partial V}{\partial t_G} + \frac{\partial V}{\partial T}\frac{dT}{dt_G} + \frac{\partial V}{\partial p_Q}\frac{dp_Q}{dt_G} \qquad \text{(A.5)}$$

Substituting (A.2)-(A.4) in (A.5) yields equation (2.12).

Deriving Equation (2.14)

We assume the standard falls on (N, L)

Consider the individual who was purchasing (N, L):

$\bar{F}$ fuel efficiency requirement

$$V(p_X, p_Q, p_M, \bar{F}, \alpha) = \max u(X, q(S,A), M, \alpha) + \lambda\left[Y - p_X X - p_L' - p_N' - \frac{p_G}{F}M\right] \qquad \text{(A.6)}$$

where:

$$p_L' = p_L + \frac{\partial p_L}{\partial \bar{F}} \quad \text{and} \quad p_N' = p_N + \frac{\partial p_N}{\partial \bar{F}} \tag{A.7}$$

The welfare effect of a marginal increment in the standard is given by:

$\frac{1}{\lambda}\frac{dV}{d\bar{F}} = -\left(\frac{dp_L'}{d\bar{F}} + \frac{dp_N'}{d\bar{F}}\right) - M\left(\frac{dp_M}{dF}\frac{dF}{d\bar{F}}\right) + \frac{dp_Q}{d\bar{F}}$, which is equivalent to equation (2.14).

Deriving Equation (2.18)

The individuals' problem is:

$$V(p_X, p_Q, S_R, t_R, T, \alpha) = \max u(X, q(S, A), M, \alpha) + \lambda\left[Y - \gamma T + S_R - p_X X - (p_Q + t_R) - \frac{p_G}{F}M\right]$$

(A.8)

The welfare effect of a marginal increase in the subsidy is given by:

$$\frac{dV}{dS_R} = \frac{\partial V}{\partial S_R} + \frac{\partial V}{\partial p_Q}\frac{\partial p_Q}{\partial S_R} + \frac{\partial V}{\partial T}\frac{\partial T}{\partial S_R} \tag{A.9}$$

Using Roy's identity and substituting into (A.9) yields 2.18.

Figure 1

Sorting of Households in Vehicle Space

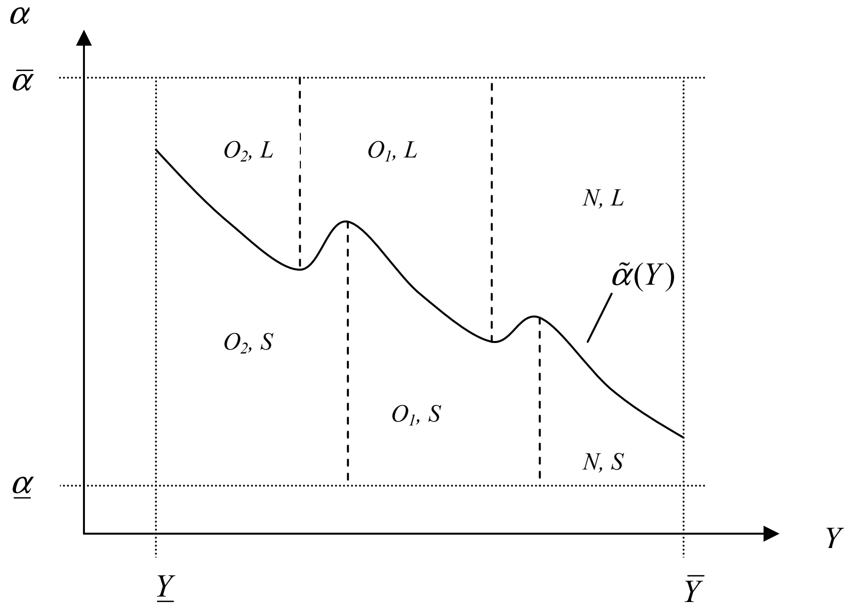

Figure 2

The Market for Used Cars

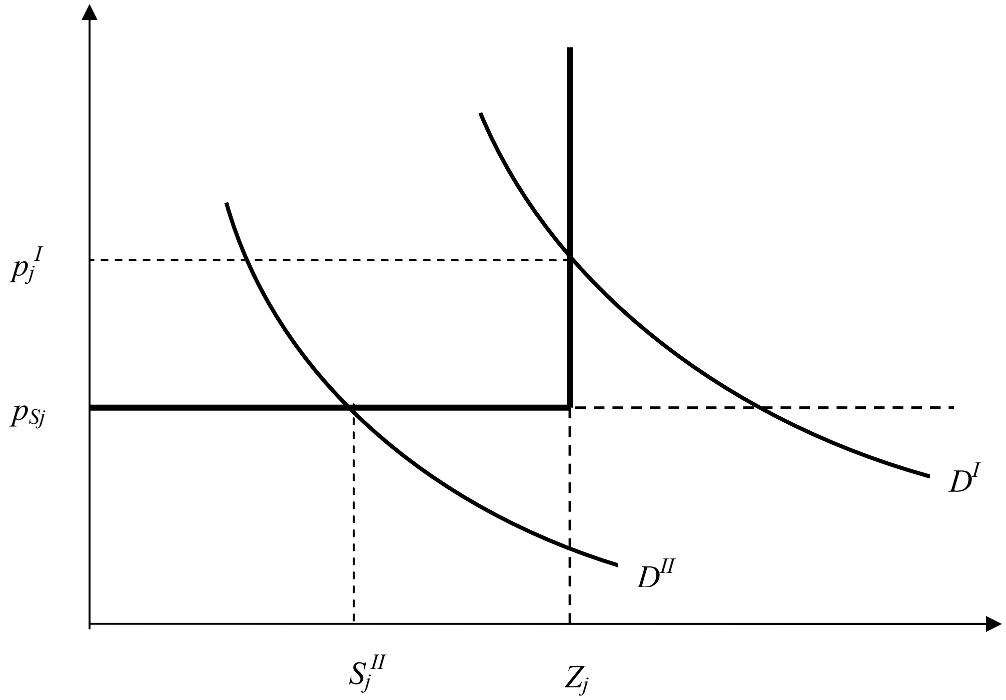

Table 1
Benchmark Prices and Quantities of Vehicles

	Benchmark
Price	
New, Small	4000.0
New, Large	4829.7
Old, Small	2242.1
Old, Large	3037.3
V. Old, Small	768.4
V. Old, Large	1526.5
Quantity (% of HH)	
New, Small	2.50
New, Large	1.90
Old, Small	23.90
Old, Large	16.60
V. Old, Small	36.30
V. Old, Large	18.80

Figure 3a

Costs of Alternative Policies in the Short Run
(Gasoline Use Target)

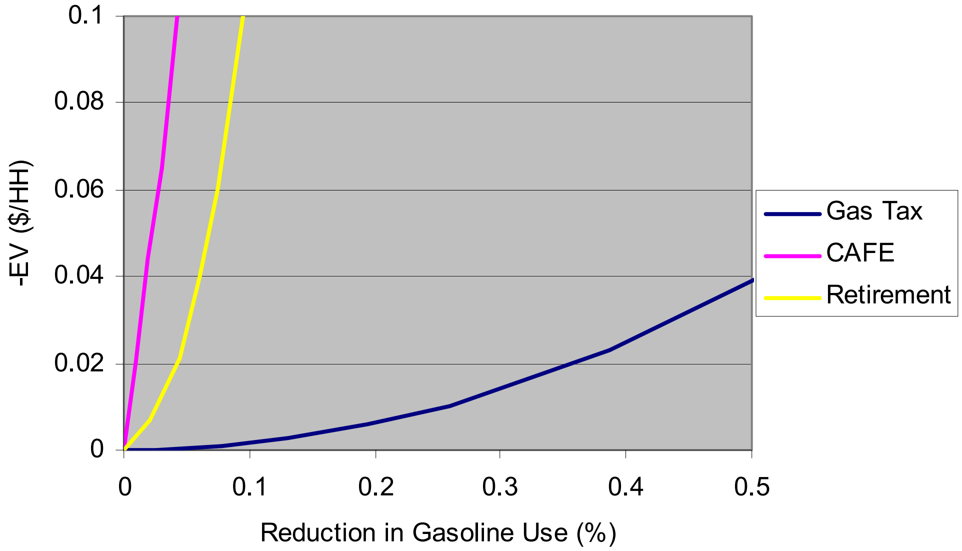

Figure 3b

Costs of Alternative Policies in the Long Run
(Gasoline Use Target)

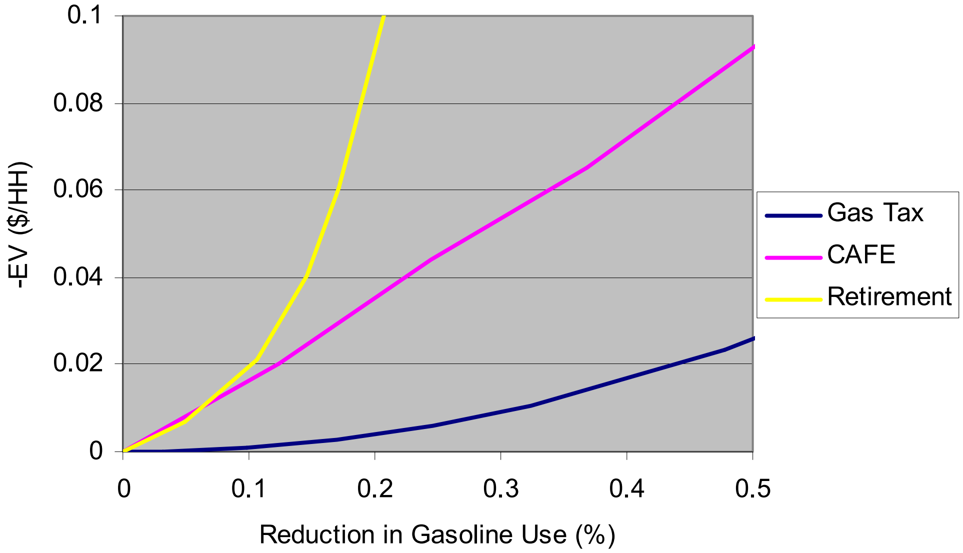

Figure 4a

Costs of Alternative Policies in the Short Run

(Pollution Reduction Target)

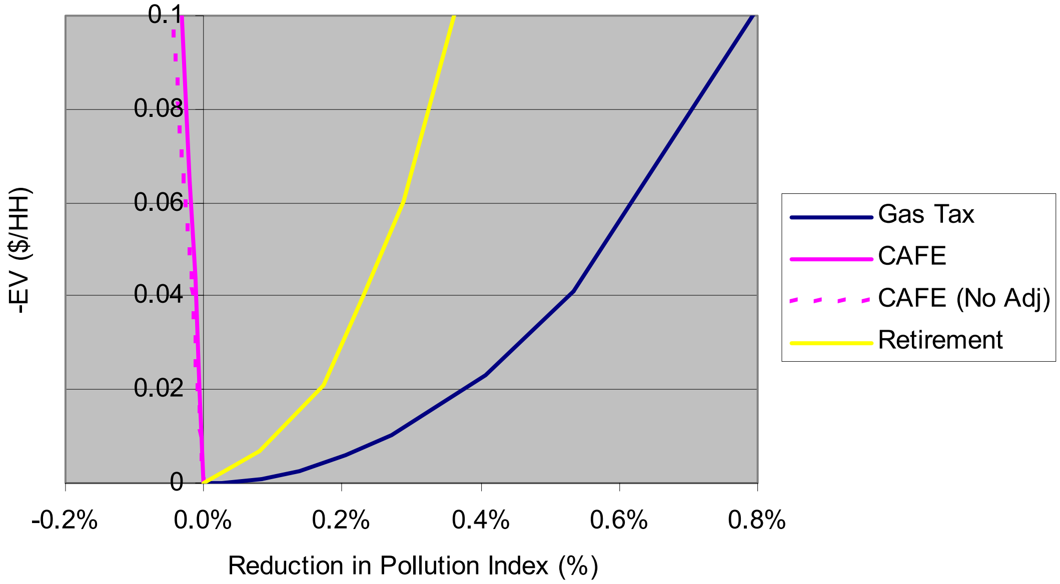

Figure 4b

Costs of Alternative Policies in the Long Run

(Pollution Reduction Target)

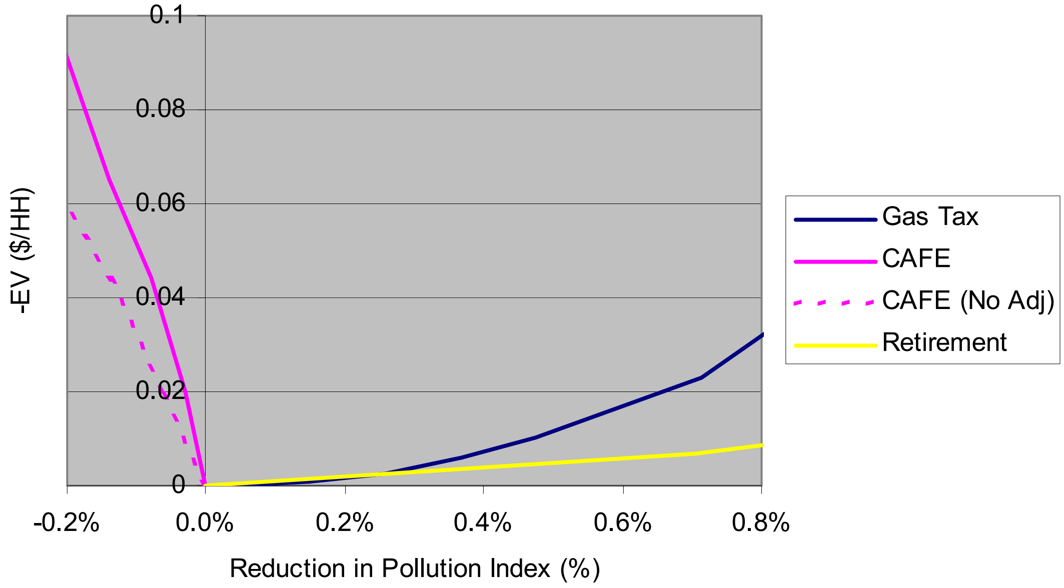

Figure 5a

Composition of the Vehicle Fleet -- Benchmark

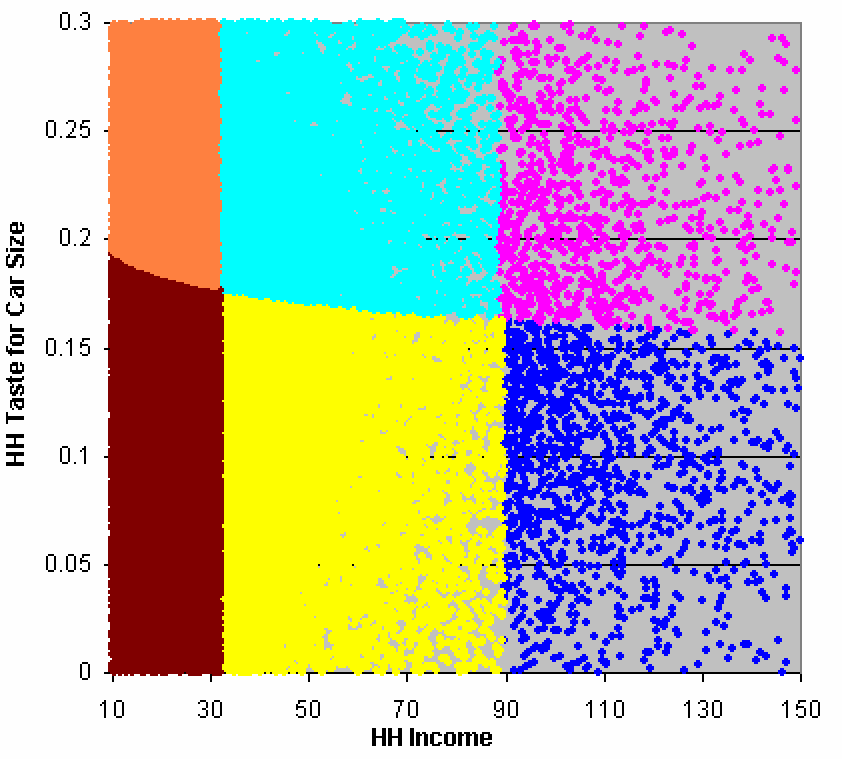

Figure 5b

Composition of the Vehicle Fleet under Gasoline Tax

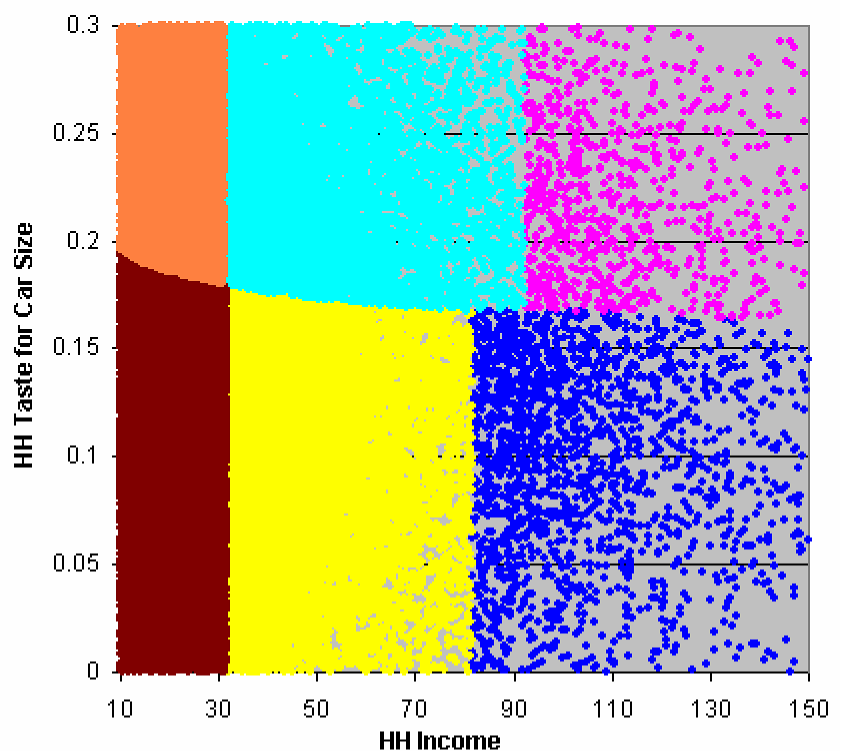

Figure 5c

Composition of the Vehicle Fleet under CAFE Standard

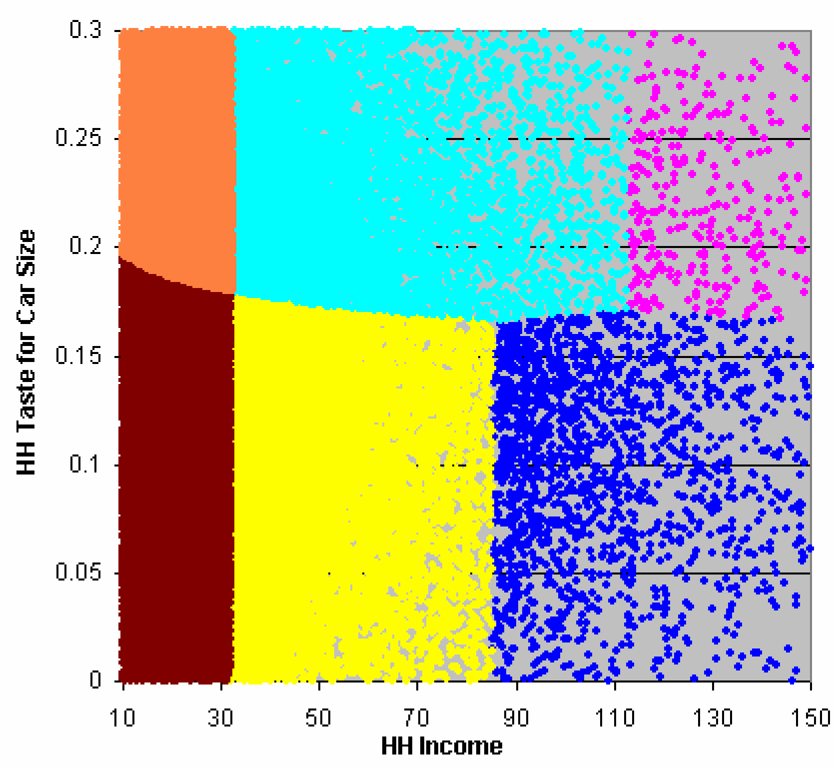

Figure 5d

Composition of the Vehicle Fleet under Retirement Subsidy

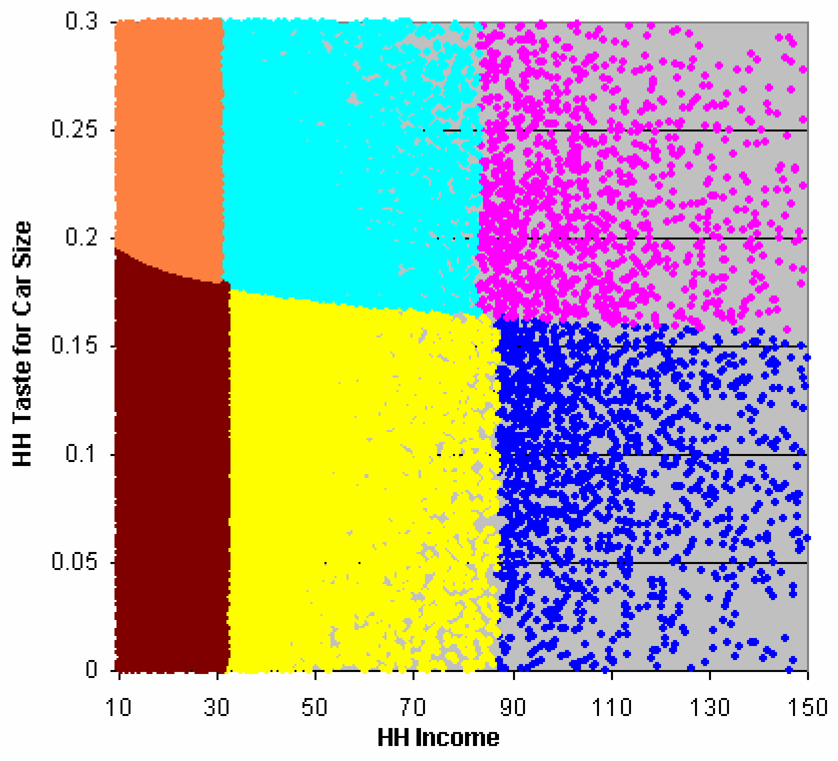

Figure 6a-1

Distributional Impacts of the Gasoline Tax
-- Constant Lump-Sum Revenue Recycling --

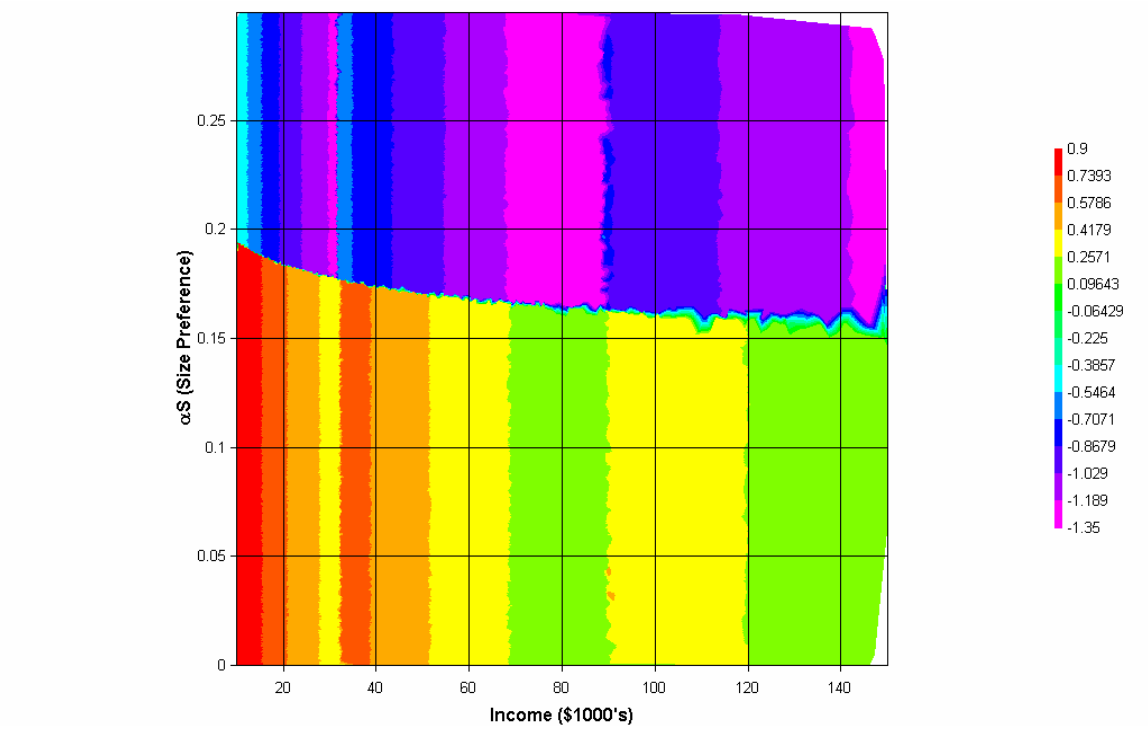

Figure 6a-2

Distributional Impacts of the Gasoline Tax
-- Income-Proportional Lump-Sum Revenue Recycling --

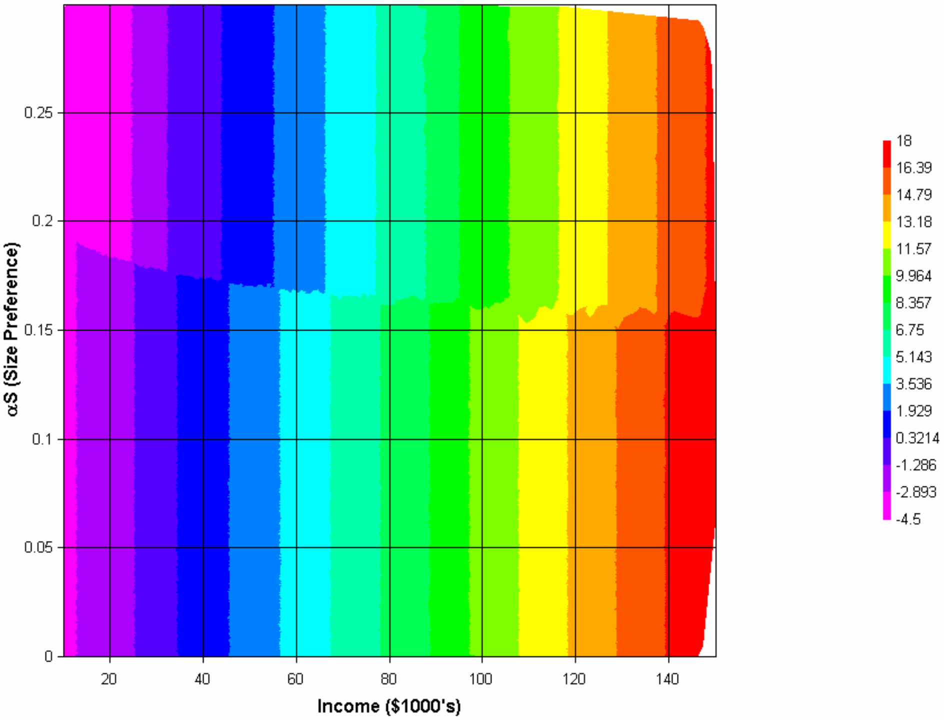

Figure 6b

Distributional Impacts under the CAFE Standard

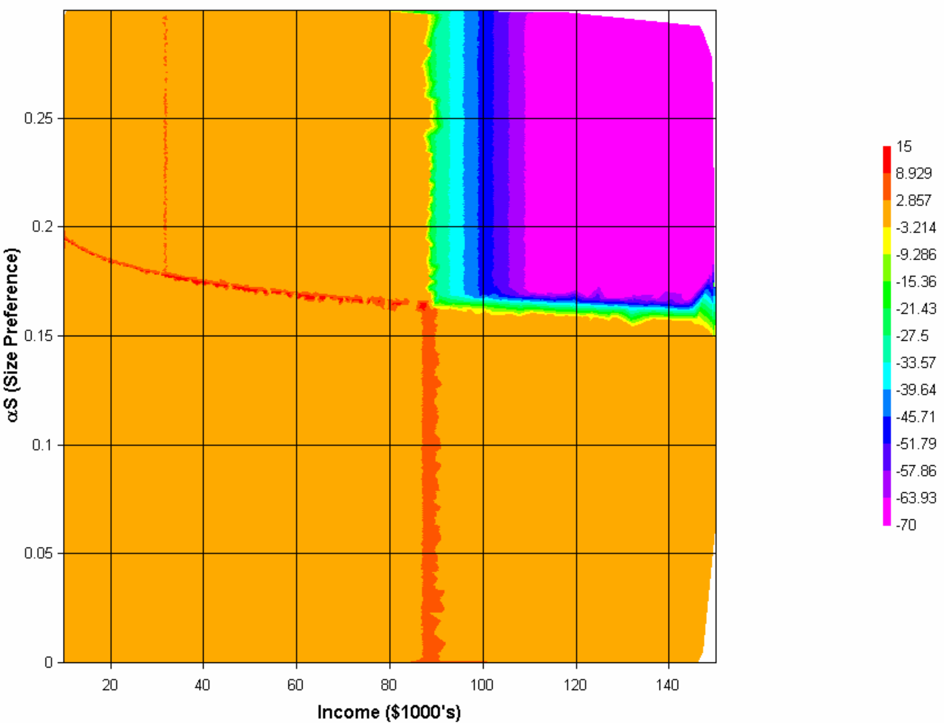

Figure 6c

Distributional Impacts under Retirement Subsidy