THE WELFARE IMPLICATIONS OF CARBON TAXES AND CARBON CAPS: A LOOK AT U.S. HOUSEHOLDS

Sumala Tirumalachetty
Transportation Analyst
Delcan Corporation
Vienna, Virginia
s.tirumalachetty@delcan.com

Kara M. Kockelman
(Corresponding author)
Professor and William J. Murray Jr. Fellow
Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin
6.9 E. Cockrell Jr. Hall
Austin, TX 78712
kkockelm@mail.utexas.edu

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ABSTRACT

Climate change has emerged as a leading environmental concern in recent years. The two widely discussed and debated options for abatement of greenhouse gas (GHG) emissions are a cap-and-trade system, at the level of producers, and an emissions tax. More interesting is the question of capping (and trading) at the level of individual households. Regardless of policy pursued, a key concern in implementing such policies relates to equity: stakeholders wish to understand the distributional or effects, whereby poorer households may be disproportionally impacted.

In this paper, household expenditure data from the U.S. Consumer Expenditure Survey are used to anticipate the economic impacts of energy taxes versus household-level emissions caps (with buy-out permitted, for those who exceed their budget) across different income classes and different types of expenditures, including those on transport. A translog utility model was calibrated to estimate demand quantities under two different tax rates and four different cap-and-trade scenarios. While the 9-category demand system does not allow for likely consumption shifts (toward less energy-intensive items) within each demand category, the model still provided a series of meaningful results. For example, the $100-per-ton case was estimated to yield the same total carbon reductions (just over 12 percent) as a cap of 15 tons per person (per year). The majority of the emissions reductions under a cap-and-trade policy are estimated to come from higher income groups, while reductions are expected to be much more uniformly distributed under a tax policy. Welfare loss (in terms of equivalent variation) as a share of income is found to be higher for lower income households when carbon taxes are implemented. In the end, a cap-and-trade policy seems most effective in reducing emissions without negatively impacting lower income households, and without worrying whether taxes will engender enough thoughtful consumption shifts to ensure steep reductions.

Keywords: Carbon emissions, Carbon trading, Carbon credits, Cap and trade, Welfare effects

BACKGROUND

Climate change has emerged as a leading environmental concern in recent years. Nations all over are debating policies to reduce emissions of carbon dioxide (CO2) and other greenhouse gases[1]. Per capita emissions in the United States were estimated to average 23.4 tons of CO2 equivalents (CO2e) in 2005, more than twice European Union levels (10.7 tons per capita) and more than four times the world average of 5.8 tons (WRI 2009). The higher U.S. levels stem from greater per-capita consumption of transport, built space, and consumer items along with lower levels of efficiency, within multiple sectors, including transport (Quadrelli and Peterson 2007).

Transportation sector's GHG emissions account for28% of all U.S. GHG emissions, and these continue to grow at a higher rate than overall emissions.[2] Many studies have examined how shifts to more efficient vehicles, greater use of less energy-intensive modes, and lower overall travel might achieve certain levels of emissions reductions (Kockelman et. al 2009, Bomberg et al. 2008). However, at the scale of national policy, the focus has been on the introduction of carbon taxes or implementation of a cap and trade strategy. Such policies affect not only transport costs and associated demands, but also imply increased prices of food, electricity and natural gas. Unfortunately, there has been little comprehensive work examining household expenditures and related GHG emissions across the entire range of goods and services that will be affected by such policies. This paper presents a framework for studying household trade-offs, impacts on travel demands, and overall emissions savings under the two policies. The next section provides more details on these policies.

CARBON TAXES AND CARBON CAPS

The U.S. Congress has been debating proposals to address greenhouse gas targets and climate change policies for several years now (e.g., McCain and Lieberman's 2005 Climate Stewardship and Innovation Act, Bingaman and Specter's 2007 Low Carbon Economy Act, and Waxman and Markey's 2009 American Clean Energy and Security Act). In 2005 the European Union (EU) established the world's first cap-and-trade system for greenhouse gas, and Canada's British Columbia and Quebec provinces have introduced carbon taxes to try and reduce emissions.The prevailing options for abatement of carbon emissions are a (upstream) cap-and-trade system and a carbon emissions tax. The "cap" refers to an upper limit on the amount of CO2e that may be emitted from the use of electricity, oil, natural gas and food production. And "trade" refers to the system in which households or firms can buy or sell the rights to emit, called credits. A market would be established so that high-level GHG producers who use need credits (beyond their allowed credits) would have to pay for these. Those who lead less energy intensive lives and/or who invest in energy efficiency are unlikely to use all their allowances and can add to their income by spending surplus units in the market. Market clearance would results in a price per ton

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[1] For background on the science of climate change and the consequences of inaction see, for example, the Intergovernmental Panel on Climate Change (2007a) and Stern (2007).

[2] Total U.S. emissions rose 13% between 1990 and 2003, while those from the transportation sector rose 24% (Brown et al. 2005).

of CO_2e so that supply matches demand. The increased cost of production would be largely passed along to consumers, depending on demand elasticities.

A tax, by contrast, is a less complex option that requires emitters to pay a tax for every ton of CO2e produced. The government would set a price per ton on carbon, which would translate to an implicit tax on gasoline, diesel, natural gas, electricity and other sources. Higher prices would induce households and firms to reduce consumption and move towards more carbon efficient lifestyles (for instance, shifting to more fuel efficient vehicles). How quickly consumers move away from higher priced goods, however, is not always clear. (For example, price elasticities on gasoline can be quite low: just -0.09 in the short-run and -0.38 in the long run, according to Small and Dender's (2007) analysis of 1966-2001 U.S. data.) A budget (or cap) on each households' GHG emissions may well serve as a much clearer target signal, engendering faster and less welfare-impacting change.

While administration of a carbon tax is relatively straightforward, a cap-and-trade policy requires more implementation effort. Taxes provide incentives (via price signals) for consumers to reduce their emissions as well as investors to move toward cleaner technologies. While the price of carbon is fixed under this strategy, total emissions are uncertain and depend on the response behavior of households, firms, investors and others. In contrast, caps mostly ensure pre-defined emissions reductions, but the price of carbon will vary with the carbon market's trading activity and levels of initial allowances provided. Moreover, more data generally are required for cap and trade policies: a key issue in the EU's 2005-2007 (upstream) carbon-permit experience was lack of data on nations' emissions inventories, resulting in over-allocation of credits (Ellerman et al. 2007). With a comprehensive emissions reporting system now in place, this and other issues are expected to be addressed in the second phase of the EU's trading scheme.

Under a cap-and-trade program, the government can issue permits for free to regulated firms (upstream approach), households (downstream), and/or other entities; auction the permits; or use some combination of free distribution and auctions. While an upstream policy is simpler to implement, it is likely to appear much like a carbon tax to consumers, in the form of higher prices, and may not have as much impact on behavior. Roberts and Thumin (2006) discuss this and other issues involved in downstream versus upstream cap-and-trade systems. The focus in this paper is on the former, to see what economic (and econometric) techniques may suggest for behavioral adaptation, welfare, and emissions reductions under the downstream cap-and-trade versus emissions tax scenarios.

POLICY IMPACTS

In choosing between policy instruments, several criteria are relevant. These are cost effectiveness (to achieve target reductions), uncertainty (of outcomes), and incidence (i.e., distributional equity across households and/or other stakeholders) (Aldy et al. 2008). The last of these is often referred to as the regressivity effect. While taxes create revenues that can address regressivity to some extent, incidence and impact really depend on policy specifics and consumer flexibility.

Though downstream cap-and-trade policies -- at the level of households -- are rarely discussed in the literature, the U.K.'s Department of Environment, Food and Rural Affairs (DEFRA) has sponsored some investigation into their feasibility and distributional impacts. As a result of such work, Thumin and White (2008) report that 71% of U.K. households in the lowest three income deciles would have surplus allowances to sell, while 55% of households in the highest three income deciles would either have to buy allowances or reduce their emissions. In other words, lower income households may well benefit from a (downstream) cap-and-trade policy. Moreover, the cost at which the market for credits will clear could be substantially lower than tax applied up top, or the implicit tax of a cap applied at the level of energy producers. Thoughtful research is needed in these areas.

A number of studies have investigated the impacts of energy and carbon taxes on household income distribution. For example, Brannlund and Nordstrom (2004) assumed a doubling of Sweden's carbon tax and compared the outcomes of two alternative recycling options: a lower overall value-added tax (VAT) and a lower VAT on public transport (equivalent to a transit subsidy). They found that both reforms are regressive, with the second one also resulting in a higher burden on households living in less populated areas. Wier et al. (2005) assessed the distributional impact of Denmark's carbon tax by combining an input-output model and national consumer survey. They found the tax to be regressive, particularly for rural households. For the Netherlands, Kerkhof et al. (2008) also found that a carbon tax is regressive. In some contrast, Tiezzi (2001) concluded that Italy's carbon tax is not regressive, but this may be because the tax lies mainly on transport fuels.

A few such studies have been conducted for the U.S. context. Lasky (2004) observed that regardless of how credits are distributed (i.e., upstream to energy producers or downstream to final consumers), most of the costs of meeting a nationwide cap on carbon emissions will be borne by consumers facing persistently higher prices for power, fuels and other high-energy products. Dinan and Rogers (2002) examined the effects of a 15% reduction in US carbon emissions, under different mechanisms for allocating emissions permits. When all costs are passed on to consumers, they estimated that a 15-percent cut in CO2 emissions would cost the average U.S. household in the lowest income quintile (i.e., lowest 20-percent) about 3.3 percent of its average income. By comparison, a household in the top quintile was estimated to pay about 1.7 percent of its average income.[3]

Here, the economic impacts of such policies across different classes of households are estimated and then compared using Consumer Expenditure Survey (CEX, 2002) data for choice behavior model calibrations. The following section provides details on all data sets used.

DATA

The Consumer Expenditure (CEX) Survey is a national level survey conducted by the US Census Bureau for the Bureau of Labor Statistics (BLS) every five years. This survey collects information on household incomes and expenditures, thereby reflecting buying habits of US consumers (BLS, 2001). In addition, information on individual and household, demographics,

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[3] Although the lowest quintile would bear the cost as a higher share of household income, it would pay the least in absolute terms.

employment status and vehicle characteristics is collected. The diary portion of the survey is a self-administered instrument that captures information on all purchases made by a consumer over a two-week period. The interview survey is conducted on a rotating panel basis, administered over five quarters, and collects data on quarterly expenditures higher cost items, in addition to soliciting information on regular purchases.

Each component of the CEX survey queries an independent and strategically sampled set of U.S. households. For this analysis, the 2002 interview survey data made available at the National Bureau of Economic Research (NBER, 2003) archive of microdata extracts was used (along with household-level expansion factors, to better match the U.S. population). NBER processes the original data to consolidate hundreds of expenditure, income, and wealth items into 109 distinct categories. Only households with complete information in all four quarters were selected for analysis. An annual household savings variable was computed by subtracting total annual expenditures from a household's net annual income. If savings were negative (which is possible when households spend more than they take home), the savings variable was set to zero. A new income variable was then computed, equal to the sum of expenditures plus savings.

The final data set has expenditure data from 4,472 households across the 109 categories, which were then aggregated into 9 expenditure categories most meaningful for this analysis. These constitute household Savings, along with household expenditures on Natural Gas, Electricity, Air Travel, Public Transport, Gasoline[4], Food Consumed in the Home, Food Consumed Outside the Home (dining out), and a category for Other expenditures (such as consumer goods, vehicle purchase and maintenance, and health care expenses). Table 1 provides (population-weighted) descriptive statistics for annual expenditures across these categories (as absolute values and as shares of total household expenditure).

The average 2002 income of households in the sample is $47,312. And transport expenditures (from Air Travel, Public Transport, and Gasoline – but not personal-vehicle purchase and maintenance, for example) are found to constitute 4.21% of a household's total expenditures, on average, with Gasoline accounting for nearly 80% of this share (since personal-vehicle travel is so much more common than air and transit use, in most households). It is interesting to contrast the relatively high variability (across households) in all three transportation expenditure categories versus the relatively low standard deviation in (and coefficient of variation for) Natural Gas and Electricity expenditures. Some households travel a great deal, while others do not; some take long vacations from time to time, while others stay local. Nearly all must heat and/or cool their home all year long, while maintaining household-sustaining appliances often non-stop.

Price data are not collected in the CEX survey data, and had to be obtained from other sources. Unit prices ($1 per unit) were assumed for Savings and Other expenditure categories, and Table 2 shows the mean and standard deviation for all other price assumptions, across the U.S.'s Northeast, Midwest, Southeast and Western regions. Consumer Price Indices (CPIs) were taken as a proxy for regional pricing for both at-home and away-from-home food-consumption categories. These BLS-provided values are normalized with respect to 1982/1984 values. Prices for air travel (per seat-mile) were obtained from quarterly airfare data released by the U.S.

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[4] This category includes diesel fuel.

Department of Transportation (DOT 2003), and public transport prices come from the National Transit Database (NTD 2003[5]). Of course, airlines (and other providers) tend to offer a wide variety of prices in any market, and it is unlikely that the average fares from these reports will match any particular fare offered to respondent households. Nevertheless, such information is useful in gauging per-mile travel cost variations across U.S. regions

METHODOLOGY

Consumer demand theory assumes that individuals choose demand quantities that maximize a (latent) utility function subject to a budget constraint. Flexible functional forms are sought to offer reasonably behavioral approximation subject to theory restrictions, such as homogeneity (to accommodate the notion of pure inflation, without impacting demand levels), summability (so that expenditures equal one's budget), and symmetry (so that compensated demands' price derivatives are symmetric). Such functions include Christensen et al.'s (1975) transcendental logarithmic (translog) (for direct and indirect utility) and Deaton and Muellbauer's (1980) Almost Ideal Demand System (AIDS) (typically used with firms' cost functions).

Obtaining standard Marshallian (uncompensated) demand functions by maximizing the direct utility function subject to budget constraints can be quite cumbersome for complex functions. By beginning from a specification of indirect utility, one can rely on a relationship called Roy's Identity (Roy 1943) to quickly arrive at individual demand equations (using the ratio of price and income derivatives).

Carbon taxes increase prices according to the intensity of each goods' carbon emissions. The demand quantities in this case can be obtained by changing prices in standard demand equations. In contrast, under a (downstream) cap-and-trade policy, households have to meet an additional carbon budget, resulting in the following utility maximization problem:

$$\max \ u(X) \text{ subject to } \bar{p}x \leq M \ and \ \bar{c}x \ \leq B \qquad (1)$$

where $u(X)$ is a differentiable direct utility function, x is a vector of n consumption goods (including electricity, gasoline and so on), $\bar{p}$ is a vector of unit prices, $\bar{c}$ is a vector of carbon emission rates, M represents the household's annual income constraint, and B is the carbon budget (in metric tons per year per household, for example).

Utility maximization under twin budgets has been applied in the case where an individual faces time and money budgets. Kockelman (2001) modeled households' consumption of various discretionary "activities" as a function of access travel times (to activity sites) and both income and time budgets. Shaikh and Larson (2003) developed a demand system for recreational activities based on the AIDS specification, with choices constrained by both money and time.

Depending on human psychology and the penalty (both monetary and non-monetary) for exceeding a cap (and the benefits of staying under a cap), the behavioral effects of such a policy may differ quite a bit from a welfare-equivalent drop in money budget. Another complexity is

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[5] The NTD (2003) relies on the average number, length and fare of transit trips from over 600 transit agencies, across the nation; these are then used to determine the average cost per mile of using public transportation.

the fact that existence of a second budget (on carbon emissions in this case) generally adds parameters to the preference specification. Without actual data points on such budget contexts, and their associated demand levels, one cannot statistically identify these added parameters. However, here households are permitted to buy their way out of their carbon budget, by paying a pre-determined carbon emissions penalty (or price, effectively) – and they benefit from consuming below their carbon budget (at the same rate). This single-price penalty translates emissions directly into dollars, so the carbon budget effectively merges with the income budget and the parameter identification question disappears.

Nevertheless, the question of how people would really respond to the presence of a second, explicit budget (even when emissions are exchangeable, at a known price) remains; actual testing of such budgets, in a thoughtfully designed lab setting or in practice would be required to tackle this largely psychological question. It is a question that can have profound implications for economic inference, but is beyond the scope of this work. (Intuitively, one might expect most households to view the second budget as a rather strict budget and strive to hit it, even if buying out is simple. As a result the emissions savings of such a policy may be much greater than this work suggests.)

In order to estimate preference functions, demanded quantities and welfare impacts under both policy settings, equation (1) is used here. Thus, this work starts from a direct utility function. Christensen et al.'s (1975) translog specification enables rather flexible examination of substitution patterns among the expenditure categories (along with non-constant expenditure shares) and so was selected for model estimation. More details on this specification can be found in Deaton and Muellauer (1980).

Direct Translog Utility Function

The translog form for (direct) utility is as follows:

$$-ln\, U = \alpha + \sum_i \alpha_i ln\, X_i + 0.5 * \sum_i \sum_j \beta_{ij} ln\, X_i\, ln\, X_j \qquad (2)$$

Maximizing utility subject to the budget constraint $(\sum_i p_i X_i = M)$, one has the following expenditure share equations:

$$\frac{p_j X_j}{M} = \frac{\alpha_j + \sum \beta_{ij} ln\, X_i}{\alpha_M + \sum \beta_M ln\, X_i} \qquad (3)$$

where $\alpha_M = \sum \alpha_K$ and $\beta_M = \sum \beta_{iK}$. Since budget shares must sum to 1.0 (i.e., households use all their income, for consumption and/or savings), additional normalization is required for unique parameter identification. The standard normalization is $\sum \alpha_K = 1$ (Jorgenson and Lau 1979).

All parameters characterizing this system of demand equations (3) were estimated using a simultaneous equations system (SES) to ensure that parameter values were consistent across equations. Since the associated *indirect* utility expression cannot be obtained (as described earlier), numerical methods were used to estimate demanded quantities under the carbon-cap scenarios. These numerical methods include calculating the Hessian for the Lagrangian from a quasi-Newton approximation.

Before turning to a discussion of methods for obtaining welfare results, it merits mention that the data aggregation process used here, and the associated functional specification, can be quite limiting for certain emissions-savings (and other) behaviors that exist. Such aggregation implies that all dollars expended within a single category are equivalent. Substitution among alternatives (e.g., those of different carbon intensity) within a category will not result in an estimate of lower carbon emissions. Of course, the Gasoline category is very homogeneous (though different prices exist within that category, thanks to different grades of automotive fuel). But categories like Air Travel and Public Transport offer different options that may be more or less efficient (e.g., large jets flying moderate distances full, or large train cars running corridors mostly empty, versus nearly full buses). And the Other category includes a tremendous diversity of energy implications (from one car to the next, one refrigerator to the next, and so forth). Households therefore have more flexibility in consumption (and emissions decisions) than the model allows for. Thus, the welfare implications of either policy (cap or tax) may well be much gentler than model results will indicate.

To address such issues, greater disaggregation from the start and/or nested utilities and demand equations, within each category (with sub-nest demands conditioned on category expenditure), would allow analysts to able to appreciate likely substitution behaviors better (e.g., from one vehicle type to another). Nevertheless, estimation of such complicated functional forms, subject to twin budgets, is far from straightforward. More microeconomic research in this area would be very useful.

Welfare Calculations

The net benefits or welfare implications of an economic policy can be rather rigorously assessed using the notion of equivalent variation (EV) (see, e.g., Varian 1992, and Small and Rosen, 1981), which represents the increase (or reduction) in income that would be equivalent to the policy change (either a carbon emissions tax or cap). In other words, it is the income change that results in the same (post-policy) level of (maximized) utility. Since, the indirect utility function associated with the system of demand equations used here (3) and its associated expenditure function cannot be directly evaluated, EV values for each household in the CEX sample were arrived at by iteratively evaluating the maximized utility expression (effectively the indirect utility), subject to different money-budget constraints. The income constraint (M) was modified until correspondence was achieved in utility values (pre- and post-policy implementation). In this way, the equivalent variation in expenditure was obtained, for each household.

SETTING CARBON TAXES AND CARBON BUDGETS

In theory, the same emissions outcomes and policy responses should be achievable via a carbon tax or a cap-and-trade system (Metcalf 2008). But carbon tax rates and carbon caps or credit limits must be designed carefully. Low tax rates may not motivate any shifts in behavior, whereas high tax rates may excessively burden low income households. One can argue that the tax should be set equal to the social cost of added GHG emissions, but such costs can be very difficult to determine, particularly with a long-term problem like climate change, fraught with uncertainty and complexity. Even marginal sequestration or GHG-avoidance costs can prove difficult to evaluate, and prices found in existing emissions trading systems may bear the marks of a political compromise. Nevertheless, Tol (2005) assessed 103 published estimates of marginal GHG costs and arrived at an average of $13.64 per metric ton of CO2e. The IPCC's Working Group II survey of 100 estimates finds a range of just $3 to $95 per ton (IPCC 2007). Metcalf (2005) recommended a carbon tax just under $17/ton of CO2, with an annual increase of 2%. And Nordhaus (2007) has concluded that a carbon tax starting at $7.40/ton of CO2 would be optimal, so long as it increases by 2 to 3% a year in real terms (after inflation), until 2050. Of course, taxes like these are quite low and may have no behavioral impacts in many sectors of the economy for many if not all households. (For example, $10 per ton translates to less than 1¢/gallon, which will have no effect on gasoline sales. [Kockelman et al. 2009])

Several EU countries have already implemented carbon taxes[6], and different taxes have been proposed in the United States[7]. In order to stabilize carbon emissions prices on GHG emissions are expected to be $25 to $70 per ton CO2e by 2020, rising to $127 to $230/ton by 2050. Here, tax rates of $50/ton and $100/ton of CO2 are imposed, to study the welfare implications across household classes (Clarke et. al 2007).

New prices on each of the nine demand categories are calculated by simply [8] adding each category's existing price (as shown in Table 1) to the product of that category's associated carbon intensity (CO2e per unit consumed) and the carbon tax rate used ($50 or $100 per ton). Energy intensity coefficients for several expenditure categories were obtained from EIA and EPA documents (EIA 2002, EIA 2005, EPA 2005), and all values used are shown in Table 3. CO2 emissions by air travel are estimated to vary from 1.21 lbs CO2 per passenger mile (for short flights) to 0.849 lb CO2 per passenger mile for long flights[9], so an average value of 0.934 lbs/mile was used here.

Here the carbon cap is set at either 10 or 15 tons, per person per year, to roughly approximate the resulting carbon emissions (per capita) that the $50 and $100 tax scenarios yield. Households with excess credits (typically estimated to be low-income and/or larger households in the CEX data set) can sell these and increase their income, while households with a binding carbon budget constraint can increase their carbon cap limit by buying credits at the same rate (either $50 or $100/ton). Though the credit cost is pre-determined (rather than market-determined) in these scenarios, the solution mechanisms used still ensure that the emissions-per-capita target is met.

ESTIMATION

Parameters for the direct translog utility function and the expenditure share equations were estimated using STATA software's nonlinear seemingly unrelated regressions (SUR) routine, but constrained to ensure parameter consistency (and thus implying an SES specification). The

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[6] For example, Sweden enacted such a tax in 1991. Currently, the tax is $150 per ton of carbon, but no tax is applied to fuels used for electricity generation, and industries are required to pay only 50% of the tax (Johansson 2000). In Finland, the current tax is €18.05 per ton of CO2 (€66.2 per ton of carbon) or $24.39 per ton of CO2.

[7] For example, Boulder, Colorado implemented the nation's first tax on gas and electricity bills (Kelley, 2006). And California regulators have been studying fee structures (see, e.g., Young 2009).

[8] The pre-determined price on GHG emissions (of $50 or $100 per ton) provides some guarantee on price for households and the governing agency, while mimic a penalty system and simplifying calculations here. Simulation of the entire market and credit-price clearance (using all CEX households, for example) would also ensure the cap is met.

[9] These estimates come from 3Degrees Group, at http://www.3degreesinc.com/calc3/methodology/.

parameters were estimated using budget share equations for 8 of the 9 categories (since summability [of all expenditures - including savings, to equal income] implies the final equation's results), and results of the estimation are shown in Table 4. Transit and air travel expenditures are less reliably estimated, exhibiting lower goodness of fit statistics; yet gasoline expenditures were quite stable. Utility function parameter estimates thus obtained were used to estimate demand quantities under the carbon caps and tax rates described earlier.

For each household, the direct utility equation (2) was maximized using MATLAB, subject to the governing constraint(s) and associated prices. Under the tax policy, there was the one, money budget constraint and the set of increased prices (as per Table 2). Under the cap-and-trade policy, the demanded quantities (and thus GHG emissions) were estimated subject to both strict money and carbon budgets (with many households emitting fewer GHGs than their carbon budget allowed), and then trading was introduced, with households allowed to sell or buy carbon credits, thus effectively increasing and decreasing their monetary budgets – along with their consumption levels (and thus their carbon footprints). The process iterates until each household has improved its utility, with no household facing a reduction in its implied utility level, and none of the households who started below their carbon budget actually exceeding their budget. In this way, the carbon cap is met by most households, but with a pre-determined cost of credits[10]. In the end, the assumptions on cap limits and credit prices lead to more households selling credits than buying them when the cap is set at 15 ton/person, and the reverse at 10 ton/person.

It should be noted that numerical estimation of maximum utility values for each household (in MATLAB) is time consuming and can lead to local optima in certain cases (roughly 5 percent of cases). To avoid this, the initial seed vector for demanded quantities was randomized to 10 values and the maximum of the resulting ten values was taken. To determine the associated welfare (EV) implications, one needs to obtain the dual of the utility maximization problem. Since minimizing monetary expenditures subject to a non-linear constraint on utility (eq. 2) is complex, line search methods were used (Fox, 1984), and this primal problem was solved for just 10% of the sample (in order to reduce estimation time, which was around 5 hours on a standard desktop computer, with 2GB memory and 3.2 GHz Processor) The results of these calculations are presented in the next section.

RESULTS

The estimation of household carbon emissions under caps versus taxes provides several interesting results. Figure 1 shows expected utility levels against household expenditures, in the base case. The utility function is non-decreasing and concave in expenditures, as economic theory suggests (see, e.g., Deaton and Muellauer 1980). Carbon emissions in all other scenarios were compared against this base scenario's results.

Figure 2 shows CO2e emissions under the different policies tested here. As shown in Figure 2a, model-predicted emissions per household appear linear with respect to expenditures under the base case and the tax scenarios (but with lesser slope in the two tax scenarios). In the all the cap-

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[10] As noted earlier, in most cap-and-trade policies the price of credits is market determined. Such flexibility adds some complication, however, in simulation of market outcomes and for households trying to optimize their consumption patterns (without knowing market price ahead of time).

and-trade combinations (shown in Figures 2b, 2c and 2d), there is a clear dispersion in predicted emissions. This dispersion is mainly due to the differences in carbon caps across household sizes, pushing 1-person households toward 10 and 15 tons of emissions (depending on the policy scenario), 2-person households towards 20 and 30 tons, and so forth. Larger households are more likely to have unused carbon credits, as household demand for shared energy services such as heating and lighting does not increase linearly with the number of occupants, while the carbon credit allocation (as modeled here) follows a linear pattern with household size.A tax of $100 per ton is predicted to reduce average carbon emissions per capitaby over 12%. Introducing a carbon cap of 10 tons (per person per year) yields the greatest GHG reduction: 19% and 23% when credits are sold/bought at $50 and $100, respectively. Thus, it seems that combining a cap with a market for credits can have substantially greater impacts. The question then becomes whether the welfare implications will favor such policy? To investigate the distributional effects, households were sorted by income, and Table 5 shows average emissions by class. The majority of GHG savings under a cap-and-trade policy is predicted to come from the highest income groups. In contrast, emissions reductions appear rather uniformly distributed (across household classes) under taxes. Under the cap-and-trade policy, lower income households are estimated to be responsible for more GHG emissions than under a carbon tax policy and the base case, thanks to the additional income these households enjoy via sales of their extra carbon allowances. Of course, as noted early in this paper, expenditures in a category of consumption do not really translate linearly to GHG emissions in that category: higher-income households may be buying more expensive clothes, more expensive cars and pricier airplane tickets than others, which would not result in proportionally higher carbon emissions. The model developed here is primarily for illustration of the evaluation methods and some basic sense of policy implications; it is not finely specified enough to detect such changes.

Table 6 provides the welfare implications (in terms of equivalent variation, EV) across the household groups, both in absolute terms and as a percentage of income. As one might expect, most households can expect to bear a cost when GHGs come under regulation. And the cap-and-trade leads to substantially higher welfare losses for higher income households than a tax policy; it thus results in higher overall welfare loss to the set of CEX households (largely because higher income households have more income to “play with”, in making an equivalency to the policy’s utility implications). Average EV is positive for the lowest income group in three of the four cap-and-trade cases, which is important to note. Not so surprisingly, carbon taxes appear regressive overall, with EV as a percentage of income higher for lower income households. Model predictions suggest that even at $50 and $100 per ton of CO2e, taxes have very little impact on the behavior of higher income households.

CONCLUSIONS AND EXTENSIONS

While taxation is commonly pursued as a policy for impacting the demand of goods carrying external costs, carbon emissions remain largely uncharted territory, with target reductions having major implications for most households and (upstream) cap-and-trade policy gathering significant support from policymakers. This paper developed a framework to estimate carbon emissions under carbon taxes as well as a downstream (household-level) form of cap-and-trade. A direct translog utility model was calibrated to provide demand quantities under various policy scenarios.

Results suggest that carbon taxes will be somewhat regressive, penalizing lower income households at a higher rate than others, and cap-and-trade policies offer an opportunity for welfare gain by many households at the lower end of the economic spectrum. However, tax revenues can address disparities while helping households save energy (via, for example, income tax deductions, subsidies for alternative modes and smarter urban design, and investments in energy efficiency at the household level). Thus, a tax policy may offset much of the impact on lower-income and/or other households. In either approach, the level of the tax or price of carbon credits must be set carefully, to be most effective.

While this work highlights several useful methods for anticipating household consumption, optimizing consumption under various policies, and anticipating welfare impacts of such policy, it lacks several useful features and presents only a partial picture of the distributional impacts of such policy. For example, controls for household characteristics (such as household size, presence of children, and age and education of household head(s)) in the demand equations should enhance prediction. In the cap-and-trade policy, the cost of carbon credits is assumed known, whereas in most policies under consideration, market forces would decide it. In addition, the translog preference specification assumes non-zero expenditures, in contrast to several of the data points. And the Other category should have some level of carbon emissions associated with it.

Perhaps the most limiting issue is that the 9-cateogory model does not allow for substitution within categories (e.g., different categories of airline travel [which then impacts air travel emissions per dollar spent], different types of vehicles owned [which then impacts fuel expenditures] and different appliances [which can affect electricity and natural gas emissions]). It and thus neglects many opportunities that households have to reduce emissions more flexibly than moving dollars across coarse categories. As different households will have different opportunities at different costs to curb their emissions, it is likely that the distributional effects will change. More consumption flexibility will also mean steeper cuts at lower welfare loss. Though the work presented here does not provide precise estimates of transportation mode shifts or vehicles owned, it provides a valuable introduction to the issues involved in modeling household responses to policy changes, along with useful methods for estimating emission savings and evaluating policy impacts under different settings. It also provides what may be a lower bound on emissions reductions and an upper bound on welfare losses under such policies. More details will be useful for policymakers and other stakeholders, as nations and communities seek optimal policy for reaching carbon targets.

REFERENCES

Aldy, J. E., E. Ley, and I. W. H. Parry. 2008. A Tax-Based Approach to Slowing Global Climate Change, Resources for the Future Discussion Paper, RFF DP 08-26. Available at http://www.rff.org/rff/Documents/RFF-DP-08-26.pdf.

Bomberg, M., K. Kockelman and M. Thompson. 2009. GHG Emissions Control Options: Assessing Transportation & Electricity Generation Technologies & Policies to Stabilize Climate Change. Proceedings of the 88th Annual Meeting of the Transportation Research Board..

Brannlund, R. and J. Nordstrom. 2004. Carbon tax simulations using a household demand model. *European Economic Review* 48, 211–233.

Brown M. A., F. Southworth, and T. K. Stovall. 2005. Towards a built climate friendly environment, Pew Center. http://www.pewclimate.org/docUploads/Buildings_FINAL.pdf Accessed 25th October 2007.

Bureau of Labor Statistics (BLS). 2003. 2002 Consumer Expenditure Interview Survey Public Use Microdata Documentation. U.S. Department of Labor Bureau of Labor Statistics, Washington, D.C. http://www.bls.gov/cex/csxmicrodoc.htm#2002.

Bureau of Labor Statistics (BLS). 2004. Consumer Expenditures in 2002. U.S. Department of Labor, Bureau of Labor Statistics, Report 974. Washington, D.C.

Christensen, L., D. Jorgenson, and L. J. Lau. 1975. Transcendental Logarithmic Utility Functions, *American Economic Review*, 53, 367-383.

Clarke, L. E., J. A. Edmonds, H. D. Jacoby, H.M. Pitcher, J. M. Reilly, R. G. Richels. 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, U.S. Climate Change Science Program. Available at http://globalchange.mit.edu/files/document/CCSP_SAP2-1a-FullReport.pdf. Accessed June 10, 2009.

Deaton, A., J. Muellauer. 1980. *Economics and Consumer Behavior*. Cambridge University Press.

Department of Transportation (DoT). 2003. United States Department of Transportation, Office of Aviation Analysis Domestic Airline Fares Consumer Report. Available at http://ostpxweb.dot.gov/aviation/x-50%20role_files/consumerairfarereport.htm. Accessed May 25, 2009.

Dinan, T, and Rogers, D. L. 2002. Distributional Effects of Carbon Allowance Trading: How Government Decisions Determine Winners and Losers. *National Tax Journal*, 55(2): 199–221.

Ellerman, A. Denny, Barbara Buchner, and Carlo Carraro. 2007. Allocation in the European Emissions Trading Scheme. Cambridge: Cambridge University Press.

Energy Information Administration (EIA). 2002. Updated State-level Greenhouse Gas Emission Coefficients for Electricity Generation. 1998-2000. http://www.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/e-supdoc.pdf. Accessed June 14th, 2008.

Energy Information Administration (EIA). 2005. Voluntary Reporting of Greenhouse Gases Program (Fuel and Energy Source Codes and Emission Coefficients). http://www.eia.doe.gov/oiaf/1605/coefficients.html.

Environmental Protection Agency (EPA). 2005. Emission Facts Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel http://www.epa.gov/OMS/climate/420f05001.pdf.

Fox, J. *Linear Statistical Models and Related Methods*. New York: John Wiley & Sons, 1984.

Intergovernmental Panel on Climate Change (IPCC). 2007a. Climate Change 2007—The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2007b. Summary for policymakers. In Climate change 2007: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds. Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge: Cambridge University Press, 7–22.

Johansson, B. 2000. Economic Instruments in Practice 1: Carbon Tax in Sweden. OECD. Available at: http://www.oecd.org/dataoecd/25/0/2108273.pdf. Date Accessed: 15th June 2009.

Jorgenson, D. W., and L.J. Lau. 1975. The Structure of Consumer Preferences. *Annals of Social and Economic Measures*. 4 (1), 49-101.

Kelley, K. 2006. City Approves 'Carbon Tax' in Effort to Reduce Gas Emissions. *New York Times*, Nov. 18.

Kerkhof, A. C., H.C. Moll, E. Drissen and H.C. Wilting. 2008. 'Taxation of multiple greenhouse gases and the effects on income distribution: A case study of the Netherlands. *Ecological Economics*, 318–326

Kockelman, K., M. Thompson and C. Whitehead. 2009. Americans' Travel Choices and their Relative Contributions to Climate Change: What Near-Term Behavioral Shifts Will Buy Us, and Opportunities for Meeting Carbon Targets. Proceedings of the 48th Annual Meeting of the Southern Regional Science Assocation, in San Antonio, and under review for publication in *J of Urban Planning & Development*.

Kockelman, K., M. Bomberg, M. Thompson and C. Whitehead. 2008. GHG Emissions Control Options: Opportunities for Conservation Report Commissioned by the National Academy of Sciences for the Committee for the Study on the Relationships Among Development Patterns, VMT, and Energy Conservation.

Lasky, M. 2003. The Economic Costs of Reducing Emissions of Greenhouse Gases: A Survey of Economic Models, U.S. Congressional Budget Office (CBO) Technical Paper 2004-4. Available at http://www.cbo.gov/ftpdocs/41xx/doc4198/2003-3.pdf.

Metcalf, G.E. 2005. Tax Reform and Environmental Taxation. National Bureau of Economic Research (NBER) Working Paper No. 11665. Cambridge, Massachusetts. Available at: www.nber.org/papers/w11665.pdf.

Metcalf, G. E. 2008. Designing a Carbon Tax to Reduce U.S. Greenhouse Gas Emissions. National Bureau of Economic Research (NBER) Working Paper No. W14375. Available at: www.nber.org/papers/w14375.pdf.

National Bureau of Economic Research (NBER). 2003. Archive of Consumer Expenditure Survey micro data extracts. Available at: http://www.nber.org/data/ces_cbo.html.

NTD 2003. National Transit Database. http://www.ntdprogram.gov. Accessed 25th April 2009.

Quadrelli, R, and S. Petersona. 2007. The energy–climate challenge: Recent trends in CO2 emissions from fuel combustion. *Energy Policy* 35, 5938-5952.

Roberts, S. and J. Thumim. 2006. A Rough Guide to Individual Carbon Trading: The Ideas, the Issues and the Next Steps. Centre for Sustainable Energy, Report to the U.K.'s Department for Environment, Food and Rural Affairs. Available at www.defra.gov.

Roy, René. 1943. *De l'Utilité: Contribution à la Théorie des Choix*. Hermann, Paris.

Small, K, A., and K. Dender. 2006. "Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect." *Energy Journal*, 28(1): 25–52.

Small, K., and H. Rosen, 1981. Applied welfare economics with discrete choice models. *Econometrica* 49, 105–130.

Stern, N. 2007. *The Economics of Climate Change*. Cambridge: Cambridge University Press.

Tiezzi, S. 2001. The welfare effects of carbon taxation on Italian households. Working Paper 337, University of Siena, Department of Economics. Available at http://ssrn.com/abstract=314726

Thumim, J and V.White. 2008. Centre for Sustainable Energy. Distributional Impacts of Personal Carbon Trading: A Report to the Department for Environment, Food and Rural Affairs (Defra), London. Available at: www.defra.gov.

Tol R.S.J. 2005. The Marginal Damage Costs of Carbon-dioxide Emissions: An Assessment of the Uncertainties. *Energy Policy 33*, 2064–2074.

Varian, H., 1992. *Microeconomic Analysis*, third ed. W.W. Norton & Company, New York.

Wier, M., K. Birr-Pedersen, H.K. Jacobsen and J. Klok. 2005. Are CO_2 taxes regressive? Evidence from the Danish experience, *Ecological Economics* 52, 239–251.

WRI. World Research Institute 2009. Climate Analysis Indicators Tool (CAIT) version 6.0. Washington, DC: World Resources Institute.. Available at http://cait.wri.org.

Young, S. 2009. California Weighs Nation's First Statewide Carbon Tax On Polluting Industries. *Huffington Post*. Available at http://www.huffingtonpost.com/2009/06/25/california-weighs-nations_n_220798.html. Accessed November 12, 2009.

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Table 1. Descriptive Statistics of the 2002 U.S. Consumer Expenditure Survey Data

Variable	Mean	Std. Dev.	Min	Max
Expenditures ($)	45,705	38436	3359	604,931
Savings ($)	15,224	28780	0	530,042
Other ($)	22,150	17049	772	333,674
Gas ($)	345.1	453.2	0	3,984
Electricity ($)	1,011	654.3	0	7,092
Air travel ($)	258.4	679.8	0	11,600
Public transport ($)	144.9	583.8	0	24,955
Gasoline ($)	1,299	980.9	0	10,704
Food at Home ($)	3,880	2166	0	21,515
Food away from Home ($)	1,389	1796	0	51,983
% of Total Household Expenditure				
Savings	23.33	24.91	0.000	96.77
Other	53.79	21.36	0.019	99.90
Gas	1.02	1.65	0.000	18.01
Electricity	3.09	2.74	0.000	32.89
Air travel	0.52	1.40	0.000	27.40
Public transport	0.36	1.19	0.000	33.87
Gasoline	3.33	2.46	0.000	22.66
Food at Home	11.39	7.42	0.000	60.74
Food away from Home	3.18	2.94	0.000	27.38

Table 2. Price Assumptions

Region	Category	Mean	Std. Dev.	Units	Notes
Northeast	Electricity	0.114	0.003	$/kWh	Average of all monthly data for 2002
Midwest	Electricity	0.082	0.005		
Southeast	Electricity	0.079	0.003		
West	Electricity	0.111	0.001		
Northeast	Gas	9.496	0.429	$/1000 cuft	Average of all monthly data for 2002
Midwest	Gas	6.796	0.395		
Southeast	Gas	8.299	0.319		
West	Gas	7.852	0.214		
Northeast	Gasoline	1.454	0.117	$/mile	Average of all monthly data for 2002
Midwest	Gasoline	1.423	0.123		
Southeast	Gasoline	1.371	0.123		
West	Gasoline	1.502	0.131		
Northeast	Food at Home	177.1	0.673	CPI (100 in 1982)	Average of all monthly data for 2002
Midwest	Food at Home	170.1	0.714		
Southeast	Food at Home	171.3	0.512		
West	Food at Home	185.4	0.884		
Northeast	Food away from Home	181.4	1.402	CPI (100 in 1982)	Average of all monthly data for 2002
Midwest	Food away from Home	175.7	1.100		
Southeast	Food away from Home	180.0	1.116		
West	Food away from Home	175.4	1.413		
Northeast	Air Travel	0.160	0.549	$/mile	Average of quarterly data for 2002
Midwest	Air Travel	0.183	0.415		
Southeast	Air Travel	0.184	0.463		
West	Air Travel	0.152	0.327		
Northeast	Public Transport	0.0452	0.1262	$/mile	Computed as (fare/trip)/(miles/trip) for each state and region
Midwest	Public Transport	0.0398	0.1594		
Southeast	Public Transport	0.0211	0.0314		
West	Public Transport	0.0227	0.0424		

Note: Price data for electricity, gas, gasoline and food categories come from www.bls.gov. Airfare data were obtained from http://ostpxweb.dot.gov/, and public transit prices come from http://www.ntdprogram.gov.

Table 3. Price Changes under Energy Taxes

	Base Prices ($ per unit)		**Carbon Emission Assumptions** (lbs per unit)		**Tax** ($ per unit, if GHG = $50/ton)	**Taxed Prices** ($ per unit)	**% Change in Price**
Gas	$8.11	1000 cuft	120	1000 cuft	$2.72	$10.83	33.56%
Electricity	0.096	kWh	1.3	kWh	0.03	0.13	30.72
Air Travel	0.17	Mile	0.934	mile	0.02	0.19	12.2
Public Transport	0.03	Mile	0.3	mile	0.01	0.04	21.14
Gasoline	1.51	Gallon	19.56	gallon	0.44	1.95	29.39
Food at Home	1	Unit	1	unit	0.02	1.02	2.27
Food outside Home	1	Unit	1	unit	0.02	1.02	2.27

Table 4. Estimation Results for Translog Demand Equations

	Natural Gas	**Electricity**	**Air Travel**	**Public Transport**	**Gasoline**	**Food Home**	**Food Outside Home**	**Savings**
α_j	-0.122	-0.092	-0.132	-0.044	-0.175	0.233	-0.130	-1.752
β_{ij} **Values**								
Natural Gas	-92.7	-24.7	-29.1	5.28	-20.7	54.6	20.8	46.9
Electricity	-24.7	-95.5	17.8	14.9	-4.13E-02	43.5	-37.0	-28.0
Air Travel	-29.1	17.8	-102.8	-24.7	22.5	41.6	29.9	46.2
Public Transport	5.28	14.9	-24.7	-76.7	-48.3	-31.0	30.6	74.6
Gasoline	-20.7	-0.041	22.5	-48.3	-12.5	-10.6	15.2	35.6
Food at Home	54.6	43.5	41.6	-31.0	-10.6	253.2	-50.2	-62.6
Food-away from Home	20.8	-37.0	29.9	30.6	15.2	-50.2	10.4	35.9
Savings	46.9	-28.0	46.2	74.6	35.6	-62.6	35.9	-279.7
Other Expenses	39.6	109	-1.343	55.2	18.8	-238.8	-55.7	130.8
R^2 Values	*0.554*	*0.656*	*0.473*	*0.294*	*0.723*	*0.754*	*0.637*	*0.762*

Table 5. Average Household CO2e Emissions (tons per year) across Household Classes

	Overall	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Class 6**
		(<20 k)	**($20-30 k)**	**($30-45 k)**	**($45-60 k)**	**($60-100 k)**	**(>$100 k)**
No. of households	444	81	86	98	66	85	28
Avg. Income	$47,619	$13,885	$24,933	$37,325	$51,896	$75,748	$147,569
Base	31.9	13.3	19.9	27.5	35.9	47.9	79.6
Tax 50*	30.0	11.7	18.6	25.4	34.0	45.8	77.2
Tax 100*	27.9	10.6	16.9	23.6	31.7	42.9	72.7
Cap-and-trade 10-50**	25.8	18.1	25.1	28.3	24.9	27.7	38.1
Cap-and-trade 10-100**	24.7	18.5	22.7	27.7	24.1	25.7	37.5
Cap-and-trade 15-50**	30.5	19.4	27.7	33.4	34.4	33.9	42.2
Cap-and-trade 15-100**	29.5	20.1	27.3	32.0	32.5	31.5	40.8

*Tax X refers to scenarios with a carbon tax of $X/ton.

** Cap-and-Trade X-Y refers to cases where household emissions are capped at X tons/person/year and can be traded at a fixed rate of $Y/ton.

Table 6. Annual Welfare Implications of Policies across Household Classes

		Class1	**Class2**	**Class3**	**Class4**	**Class5**	**Class6**
EV	**All Households**	**(<$20k)**	**($20-30k)**	**($30-45k)**	**($45-60k)**	**($60-100k)**	**(>$100k)**
No. of households	444	81	86	98	66	85	28
Avg. Income	$47,619	$13,885	$24,933	$37,325	$51,896	$75,748	$147,569
Tax 50*	-$1,,457	-448.3	-892	-976	-1,258	-1,588	-7,,859
Tax 100*	-$2812	-1056.5	-1,668	-2400	-3,231	-4,262	-7463
Cap-and-trade 10-50**	-$13,381	347	-4,706	-6216	-13,151	-27,421	-60,536
Cap-and-trade-10-100**	-$13,369	380	-564	-5,502	-16,946	-31,183	-67,596
Cap-and-trade 15-50**	-$11,006	466	-2,548	-6,446	-10,464	-21,256	-50,708
Cap-and-trade 15-100**	-$11,101	345	-2,469	-5,313	-11,592	-22,715	-54,565
EV as a % of income							
Tax 50*	-2.9%	-3.2%	-3.7%	-2.6%	-2.4%	-2.1%	-3.7%
Tax 100*	-6.5%	-7.5	-6.7	-6.5	-6.1	-5.7	-5.5
Cap-and-trade 10-50**	-11.4%	2.1	-12.7	-16.6	-24.8	-36.0	-44.3
Cap-and-trade-10-100**	-20.8%	2.7	-2.1	-14.3	-31.6	-40.7	-49.1
Cap-and-trade 15-50**	-18.4%	6.8	-10.8	-17.7	-19.8	-28.2	-36.4
Cap-and-trade 15-100**	-14.7%	8.1	-8.4	-13.8	-22.0	-30.0	-38.8

*Tax X refers to scenarios with a carbon tax of $X/ton.

** Cap-and-Trade X-Y refers to cases where household emissions are capped at X tons/person/year and can be traded at a fixed rate of $Y/ton.

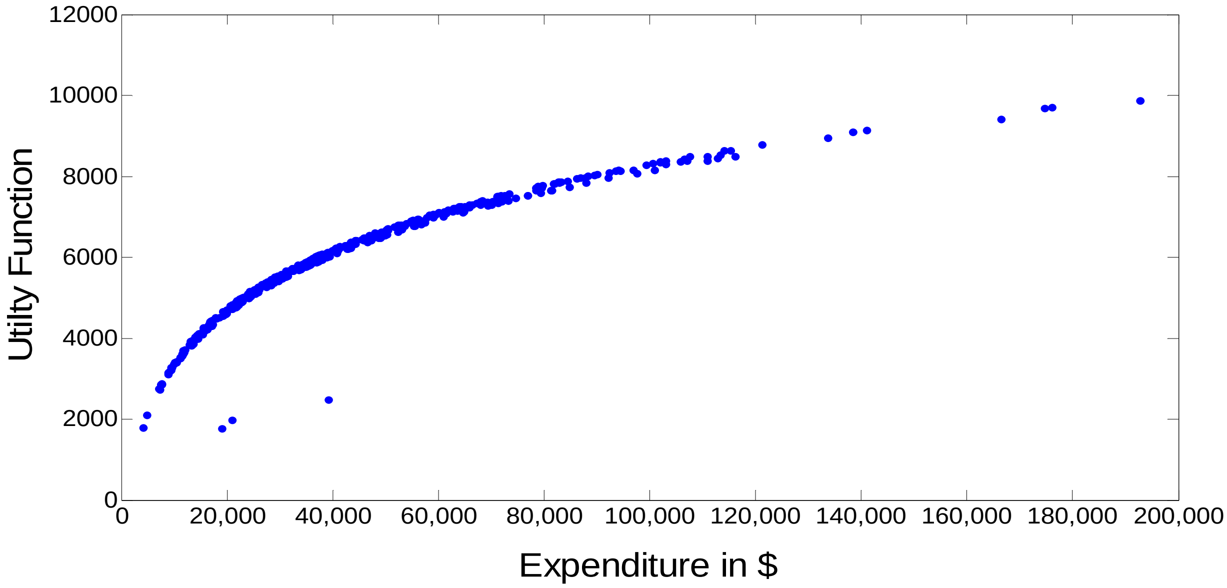
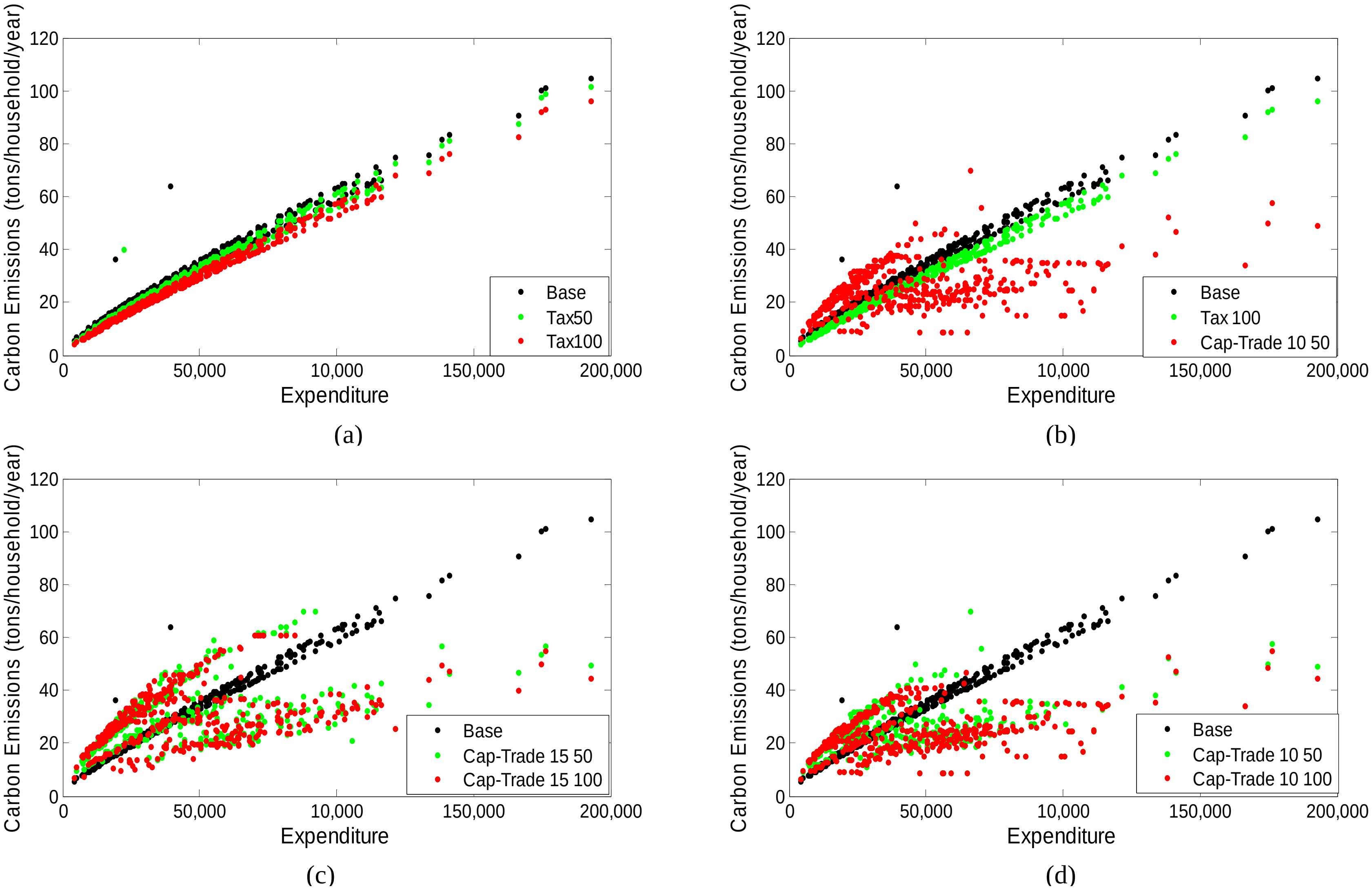


Figure 1. Household Utility versus Annual Household Expenditures



(a) (b) (c) (d)

Figure 2. Comparison of Carbon Emissions (tons/household/year) under Different Scenarios