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Optimal taxation and cross-price effects on labor supply: Estimates of the optimal gas tax ☆

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Abstract

This study estimates parameters necessary to calculate the optimal second-best gasoline tax, most notably the cross-price elasticity between gasoline and leisure. Prior theoretical work indicates the importance of this elasticity, but despite this, almost none of the prior studies of commodity taxation (and none of the studies on second-best environmental regulation) actually estimate it. Using household data, we find that gasoline is a relative complement to leisure, and thus that the optimal gasoline tax is significantly higher than marginal damages-the opposite of the result suggested by the bulk of the prior literature. Indeed, even if there were no externalities at all associated with gasoline, the optimal tax rate would still be almost equal to the average gas tax rate in the U.S. Following this approach to estimate cross-price elasticities with leisure could strongly influence estimates of optimal rates for other important commodity or pollution taxes.

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As first shown by Corlett and Hague (1953), optimal commodity tax rates depend crucially on the cross-price elasticity with leisure. Leisure cannot be taxed, and thus individuals consume more than the efficient amount of it. However, government can implicitly tax leisure by raising taxes on goods that are more complementary to leisure than is the average good and lowering taxes on goods that are more substitutable for leisure. Subsequent theoretical work extends this basic insight to more complex models of taxation.[1] But despite the theoretical importance of this elasticity, almost none of the empirical studies of commodity taxation estimate it: nearly all assume that leisure is separable from other goods in utility, and many even assume that labor supply is fixed.

In this paper, we focus on the gas tax, which is one of the most important practical examples of a differentiated commodity tax: in the U.S., it raises more revenue than any other commodity tax at both state and federal levels, and it accounts for an even larger share of revenue in other nations.[2] It also plays an important role as a corrective tax, since gasoline use entails many negative externalities, including pollution, traffic congestion, and vehicle accidents.

We estimate the cross-price elasticity between gasoline and leisure, along with other important parameters, and calculate the optimal gas tax based on these estimates. We use household-level data from the 1996–1998 Consumer Expenditure Surveys, merged with price data from the American Chambers of Commerce Researchers' Association (ACCRA) cost of living index and tax data from the National Bureau of Economic Research (NBER) TAXSIM model. We employ Deaton and Muellbauer's (1980) Almost Ideal Demand System (AIDS), which does not impose separability, unlike most other widely used demand systems.

We find that gasoline is a leisure complement, and thus that the optimal gas tax exceeds the marginal external damage associated with gas use by roughly 35%. Even if gasoline use entailed no negative externalities at all, the optimal gas tax would still almost equal the average rate in our sample. One possible explanation for this complementarity is that driving is a relatively time-intensive good, and time-intensive goods tend to be leisure complements, as suggested by Becker (1965). Another possible explanation is that the demand for leisure driving is much more elastic than is the demand for commuting.

These results clearly illustrate the practical importance of estimating the cross-price elasticity with leisure when calculating optimal tax rates—something no prior study has done. To our knowledge, Madden (1995) is the only previous empirical study on commodity taxes that focuses on the cross-price elasticity with leisure.[3] Contrary to our results, it concludes that this elasticity is relatively unimportant. Diewert and Lawrence (1996) also estimate this elasticity, but do not specifically focus on it, so its influence on their results is unclear.[4] Both studies rely on aggregate time-series data sets, which are limited by small sample sizes and highly collinear prices. Moreover, estimates based on such data are subject to aggregation bias.[5] Because our household-

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[1] For examples, see Mirrlees (1976), Christiansen (1984), and Saez (2002).

[2] In this context, "differentiated" refers to differences in tax rates across different goods, not spatial differences in gas tax rates that might be justified by differences in marginal external costs across cities or regions.

[3] This study divides consumption goods into ten categories: food, alcohol, tobacco, clothing and footwear, fuel and power, petrol, transport and equipment, durables, services, and other goods. It does not report cross-price elasticities between these goods and leisure. Other work focuses on the effects of nonseparability among consumption goods (e.g., Ray, 1986; Decoster and Schokkaert, 1990), and nearly all recent studies on commodity taxation allow this sort of nonseparability. But these studies still assume that leisure is separable or that labor supply is fixed.

[4] Each of these studies considers only the effects of marginal tax reforms, and does not report optimal taxes, so their results are not strictly comparable to ours. But the two concepts are closely related, and both depend in the same way on the cross-price elasticity with leisure.

[5] Blundell et al. (1993) studies this problem, and concludes that "aggregate data alone are unlikely to produce reliable estimates of structural price and income coefficients." (p. 570).

level data provide both cross-section and time-series variation, we can employ a more flexible functional form for demand, and our estimates should be much more precise. The latter advantage is difficult to confirm, however, because ours is the first study to report confidence intervals for its optimal tax estimates.

Because of gasoline's role as a corrective tax, this paper also makes an important contribution to the literature on second-best optimal environmental regulation. Theoretical work in this area has shown that the optimal pollution tax depends on the cross-price elasticity between polluting goods and leisure, for exactly the same reason that optimal commodity taxes do.[6] But empirical papers have not previously estimated this elasticity. We provide the first estimate of the cross-price elasticity between a polluting good and leisure, and examine its implications for environmental taxation. The bulk of the prior work in this literature suggests that the optimal tax on a polluting good will typically be less than marginal pollution damage. In contrast, as noted above, we find that the optimal gas tax substantially exceeds marginal damage.

Thus, for both literatures–on optimal commodity taxes and on optimal environmental regulation–this study demonstrates the need to explicitly estimate cross-price elasticities with leisure, rather than simply making assumptions such as separability that pin down that elasticity. And recent theoretical work shows that the cross-price elasticity with leisure influences optimal policy in many contexts other than taxation and environmental policy.[7] Our results suggest that it could be important to estimate this elasticity in those other contexts as well.

The next section of this paper develops a simple theoretical model and derives an expression for the optimal commodity tax on a good with an associated externality. Subsequent sections describe the empirical model, data, estimation results, and the implied optimal tax rate. The final section presents conclusions and suggests directions for future research.

1. A theoretical model

This section presents a simple theoretical model and uses it to derive an expression for the optimal tax on a good with an associated negative externality. This model resembles those used in recent studies of second-best optimal environmental taxes, but differs in two respects: it does not assume that leisure is separable, that the utility function is homothetic, or that the polluting good is an average substitute for leisure; and it allows for multiple households (and multiple individuals in a household), rather than assuming a representative agent.[8]

The model is also very similar to most models used in the optimal commodity tax literature. But it differs in that it incorporates an externality, includes only two produced goods, and ignores distributional considerations. We include the externality because the gas tax is an important corrective tax as well as a commodity tax. It would be simple to extend our model to allow more goods or to consider distribution, but since our primary focus is on the influence of the cross-price elasticity with leisure, we keep the rest of the model as simple as possible.

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[6] For examples, see Bovenberg and Goulder (2002). Kim (2002) focuses specifically on this issue.

[7] See, for example, Browning (1997) on the welfare cost of monopoly, Goulder and Williams (2003) on the excess burden of taxation, Parry (1999) on agricultural policy, or Williams (1999) on trade policy.

[8] We allow multiple households not because of distributional considerations, but simply because the aggregate demands in our empirical model do not equal the demand of a representative household (as is briefly discussed in the next section). Recent papers that use models similar to ours include Goulder et al. (1999) and Parry et al. (1999). Both assume a representative agent and assume that the polluting good is an average substitute for leisure in order to calculate optimal tax rates.

Each household in the economy consumes a dirty (i.e., polluting) good (D), a clean good (C), and a government-provided public good (G). The utility function for household h is

$$U^h(\mathbf{l^h}, C^h, D^h, G) - \phi^h(D), \tag{1}$$

where U is continuous and quasi-concave and the function ϕ^h represents the disutility from an externality associated with the economy-wide total consumption of the dirty good.[9] The elements l^{hi} of the vector $\mathbf{l^h}$ represent hours of leisure for each of the adults in the household.[10] The time constraint for individual i is

$$\overline{L} = L^{hi} + l^{hi}, \tag{2}$$

where $\overline{L}$ is the time endowment and L^{hi} is hours worked. The household budget constraint is

$$p_C^h C^h + p_D^h D^h = Y^h \equiv I^h + \sum_i w^{hi} L^{hi}, \tag{3}$$

where w is the after-tax wage, I is after-tax non-labor income, and Y^h is total after-tax income, which equals total expenditure. The consumer price of the dirty good (p_D) is given by

$$p_D^h = \overline{p}_D^h + \tau_D, \tag{4}$$

where $\overline{p}_D$ is the producer price and τ_D is a unit tax on the dirty good. The clean good is untaxed, and thus its producer price ($\overline{p}_C$) and consumer price (p_C) are equal.[11] The after-tax wage is

$$w^{hi} = \overline{w}^{hi} - \tau_L^{hi}, \tag{5}$$

where $\overline{w}$ is the pre-tax wage and τ_L is the marginal tax per unit of labor. After-tax non-labor income is given by

$$I^h = \overline{I}^h - T^h, \tag{6}$$

where $\overline{I}$ is pre-tax non-labor income and T is a lump-sum tax or transfer.[12]

Each of the three goods is produced under perfect competition with constant returns to scale. We assume that non-labor income is derived from ownership of a fixed factor that is a perfect substitute for labor.[13] These assumptions imply that the pre-tax wage and all producer prices are exogenously fixed and that the aggregate production constraint is

$$\sum_h \left(\overline{I}^h + \sum_i \overline{w}^{hi} L^{hi} \right) = \overline{p}_G G + \sum_h \left[\overline{p}_C^h C^h + \overline{p}_D^h D^h \right], \tag{7}$$

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[9] For simplicity, we assume that the damage from the externality appears only as a separable term in utility. If damages were to enter in some other form, that could also affect labor supply and thus influence the optimal tax rate. See Bovenberg and van der Ploeg (1994) and Williams (2002, 2003) for further discussion on this point.

[10] Throughout this paper, we use "leisure" as a shorthand term for all non-market time. Thus, it includes not just true leisure time, but also time spent on other non-market activities, such as household production.

[11] This assumption entails no loss of generality, because any tax system that taxes the clean good can be renormalized as a system with a higher income tax and no clean good tax.

[12] Note that τ_L and T could represent a linear tax system or a (household-specific) local linear approximation to a nonlinear tax system.

[13] This is unrealistic, but provides a simple way to model non-labor income. For a similar model in which the fixed factor isn't a perfect substitute for labor, see Williams (2002). The model in Bovenberg and Goulder (1996) has non-labor income derived from capital, but is far more complex and thus cannot be solved analytically.

where $\overline{p}_G$ is the producer price of the public good. The government's budget constraint is

$$\sum_h \left[\tau_D^h D^h + \sum_i \tau_L^{hi} L^{hi} + T^h \right] = \overline{p}_G G. \tag{8}$$

The level of the public good is assumed to be fixed, with any change in revenue from the dirty good tax offset by adjusting τ_L and T.[14] These adjustments follow

$$\tau_L^{hi} = \hat{\tau}_L^{hi} + \tau_Y(\overline{w}^{hi} - \hat{\tau}_L^{hi}) \text{ and } T^h = \hat{T}^h + \tau_Y(\overline{I}^h - \hat{T}^h), \tag{9}$$

where $\hat{\tau}_L^{hi}$ and $\hat{T}^h$ are constant, and τ_Y adjusts to hold government revenue constant as τ_D varies. Eq. (9) implies that the reduction in household h's taxes from a decrease in τ_Y will be proportional to Y^h. This could represent adjusting a broad-based consumption tax, renormalized as an income tax, or could represent an income tax cut that is proportional to after-tax income.[15]

Each household maximizes utility (1) subject to its time constraint (2) and budget constraint (3), taking as given prices, tax rates, the level of the public good, and the level of pollution. This yields the first-order conditions

$$\partial U^h / \partial C^h = p_C^h \lambda^h; \partial U^h / \partial D^h = p_D^h \lambda^h; \partial U^h / \partial l^{hi} = w^{hi} \lambda^h, \tag{10}$$

where λ^h is the marginal utility of after-tax income. Together with the constraints given previously, these implicitly define the (uncompensated) demand functions

$$C^h(p_C^h, p_D^h, \mathbf{w}^h, I^h); D^h(p_C^h, p_D^h, \mathbf{w}^h, I^h); l^{hi}(p_C^h, p_D^h, \mathbf{w}^h, I^h). \tag{11}$$

To derive an expression for the aggregate change in utility from a change in the tax on the dirty good, we take the total derivative of utility (1) with respect to τ_D, sum over households, substitute in the first-order conditions (10), subtract the total derivatives with respect to τ_D of the time constraint (2) and aggregate production constraint (7), and rearrange terms. This gives

$$\sum_h \frac{1}{\lambda^h} \frac{\mathrm{d}U^h}{\mathrm{d}\tau_D} = \sum_h \left[(\tau_D - \theta) \frac{\mathrm{d}D^h}{\mathrm{d}\tau_D} - \sum_i \tau_L^{hi} \frac{\mathrm{d}l^{hi}}{\mathrm{d}\tau_D} \right], \tag{12}$$

where θ is the marginal external damage (MED) per unit of D, measured in money units:

$$\theta = \sum_h \frac{1}{\lambda^h} \frac{\partial \phi^h}{\partial D}. \tag{13}$$

Expression (12) equals the change in deadweight loss in the two distorted markets: the distortion in the dirty good market $(\tau_D - \theta)$ times the change in dirty good consumption, plus the distortion in the labor market (τ_L) times the change in labor supply. This is a pure efficiency measure; as previously noted, we do not consider distributional issues in this paper.

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[14] Gasoline taxes in the U.S. are specifically earmarked for highway spending, but a gas tax in the range that we consider in this paper would raise substantially more revenue than is needed to fund highways. Thus, at the margin, gas tax revenue would flow into the general government budget.

[15] We choose this approach for adjusting the income tax because it implies that raising the dirty good tax and lowering the income tax will not shift the tax burden from labor to non-labor income or vice-versa. Because our model is static, it is not well-suited for estimating either how the tax burden would shift or what the efficiency effects of that shift would be. Thus we do not want the model's results to be driven by such effects. The results would be similar if the added revenue were used to purchase more of the public good, as long as the level of the public good is close to the optimum.

The total derivatives in Eq. (12) include not only the effect of the increase in the dirty good tax, but also the effect of the resulting income tax cut. This makes little difference for the dirty good, where the effect of the income tax change will be tiny relative to the effect of the dirty good tax, but will be much more important for labor supply. Thus, it is useful to rewrite the term for the labor market in Eq. (12) in terms of $\partial l/\partial p_D$ rather than $\mathrm{d}l/\mathrm{d}p_D$. To do this, we first define η, which is the marginal cost of public funds (MCPF). As shown in Appendix A, η is given by

$$\eta = \sum_h Y^h \Big/ \sum_h \left[Y^h + \sum_i \tau_L^{hi} \left(\frac{\partial l^{hi}}{\partial I^h} I^h + \sum_j \frac{\partial l^{hi}}{\partial w^{hj}} w^{hj} \right) \right]. \tag{14}$$

This is the marginal cost to households of raising government revenue via the income tax; thus, it is the ratio of the loss to households to the revenue raised for a marginal increase in this tax.[16] We can then find the optimal tax rate by setting the rewritten version of Eq. (12) (see Appendix A for this expression) equal to zero and solving for τ_D^*. This gives

$$\tau_D^* = \frac{\theta}{\eta} + \sum_h \left[\sum_i \tau_L^{hi} \frac{\partial l^{hi}}{\partial p_D^h} - \frac{\eta - 1}{\eta} D^h \right] \Big/ \sum_h \frac{\mathrm{d}D^h}{\mathrm{d}\tau_D}. \tag{15}$$

The first term in this expression is the externality-correcting portion of the optimal tax, equal to marginal damage divided by the MCPF. In an otherwise undistorted economy, this term would simply equal marginal damage; this rate would fully correct the externality. But in a second-best economy, the optimal tax rate represents a compromise between the rate that would fully correct the externality and the rate that raises revenue most efficiently. Thus, the more important government revenue is (i.e., the higher the MCPF), the smaller this term will be.

The second term is the tax rate that would be optimal if there were no externality, which depends on the cross-price elasticity between the dirty good and leisure. When the dirty good is a stronger substitute for leisure than is the average good, this term is negative and thus decreases the optimal tax on the polluting good. If the dirty good is a weaker-than-average leisure substitute or a complement to leisure, this term is positive and thus increases the optimal tax.

Many papers on commodity tax reforms assume that labor supply is fixed (see Ahmad and Stern, 1984, and the subsequent work that it inspired). This is also the implicit assumption in first-best studies of environmental policy. It would imply that the optimal tax in the absence of any externality–the second term in Eq. (15)–equals zero and that $\eta = 1$. Thus, the optimal tax simply equals the marginal damage from the externality (θ). In this case, raising revenue entails no distortion, so the optimal tax is just the level that fully corrects the externality.

The recent literature on second-best optimal environmental taxes allows labor supply to vary, but typically assumes that utility is homothetic and that leisure is separable–or, equivalently, that the polluting good is an average substitute for leisure. In this case, even though the cross-price elasticity with leisure is not zero, there is no need to estimate it, because it is a simple function of the own-price labor supply elasticity. Just as in the case of fixed labor supply, this implies that the optimal tax in the absence of an externality equals zero, but does not restrict η. Therefore the optimal tax in this case is θ/η.

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[16] This definition of the MCPF considers only effects in the labor market; it omits the effects of changes in environmental quality and changes in revenue from the environmental tax resulting from a change in the income tax. This expression for the MCPF and those typically used in the prior literature differ slightly because of differences in model assumptions. They are equivalent for the special case of this model that matches the typical assumptions in the prior literature: only one household, only one individual in that household, and no non-labor income.

Finally, some studies assume that leisure is separable in utility, but do not impose homotheticity.[17] This is the weakest of the assumptions commonly used in prior work, but is still very restrictive: prior estimates of the joint demand for goods and leisure decisively reject separability.[18] But it is still commonly used, because it allows the calculation of optimal taxes without including labor supply in the estimation at all, and because of the perception (due at least in part to Madden, 1995) that imposing separability has little or no practical effect on the results of studies of commodity taxation. Imposing separability allows the derivative of leisure demand with respect to the price of the dirty good to be expressed as

$$\frac{\partial l^{hi}}{\partial p_D^h} = -D^h \left[\frac{\partial l^{hi}}{\partial I^h} + \varepsilon_{DX}^h \sum_j \frac{w^{hj}}{Y^h} \left(\frac{\partial l^{hi}}{\partial w^{hj}} - \frac{\partial l^{hi}}{\partial I^h} L^{hj} \right) \right], \tag{16}$$

where ε_{DX} is the expenditure elasticity of demand for gasoline. This implies that a luxury must be a relative substitute for leisure, while a necessity must be a relative complement to leisure.

2. An empirical model

The optimal tax rate in Eq. (15) depends on several own-price and cross-price derivatives of demand. In this section, we first specify the demand system that we use to estimate these derivatives. Then we describe the data, variable derivation, and summary statistics. Finally, we discuss the estimation technique and system estimation results.

2.1. Specification of the demand system

We use the Almost Ideal Demand System (AIDS), as derived in Deaton and Muellbauer (1980). The system is defined over gasoline (the dirty good), leisure, and a composite of all other goods (the clean good). The AIDS provides a first-order approximation to any demand system, satisfies the axioms of choice, and does not assume separability or homotheticity.

In their budget share form, the AIDS demand equations for household h are

$$\begin{gathered} s_j^h = \alpha_j^h + \sum_k \gamma_{jk} \log p_k^h + \beta_j \log(y^h/P^h) \\ j,k = \text{gasoline, leisure, other goods}; h = 1, \ldots, H \end{gathered} \tag{17}$$

where s_j^{h} is the expenditure share for good j, α, β, and γ are parameters to be estimated, y^h is full income (total spending on gasoline, leisure, and other goods),[19] and P^h is the price index

$$\log P^h = \alpha_0 + \sum_j \alpha_j^h \log p_j^h + \frac{1}{2} \sum_k \sum_j \gamma_{jk} \log p_j^h \log p_k^h. \tag{18}$$

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[17] This is a common set of assumptions in the optimal commodity tax literature, starting with Atkinson and Stiglitz (1972). Studies of environmental taxation that make this assumption include Jorgenson and Wilcoxen (1993), Parry and Small (2005), and Ballard et al. (2005).

[18] See, for example, Abbott and Ashenfelter (1976), Barnett (1979), or Browning and Meghir (1991).

[19] Please note two slight notational changes from the previous section. First, that section denoted goods with the letters D, l, and C. For compactness, this section uses subscript j to index goods. Second, full income (y^h) includes the value of leisure consumed, which isn't included in income (Y^h) as defined in the previous section.

Demand theory imposes several restrictions on the parameters of the model, including:

$$\text{(19a)}\ \sum_j \alpha_j^h = 1 \quad \text{(19b)}\ \sum_j \gamma_{jk} = 0 \quad \text{(19c)}\ \sum_j \beta_j = 0 \quad \text{(19d)}\ \gamma_{jk} = \gamma_{kj}. \tag{19}$$

Under these restrictions, Eq. (17) represents a system of demand functions that add up to full income, are homogeneous of degree zero in prices and full income, and satisfy Slutsky symmetry.

Use of the price index in Eq. (18) requires estimation of a nonlinear system of equations. To simplify estimation, Deaton and Muellbauer (1980) suggests the linear approximation[20]

$$\log P^h \cong \sum_j s_j^h \log p_j^h. \tag{20}$$

This price index, however, is not invariant to changes in units of measurement (see Moschini, 1995). We therefore normalize prices to obtain the unit-invariant price index

$$\log P^h \cong \sum_j s_j^h \log(p_j^h / \overline{p}_j), \tag{21}$$

where $\overline{p}_j$ is the mean price over all households.

2.2. Data, variable derivation, and summary statistics

Our data come mainly from the 1996 through 1998 Consumer Expenditure Surveys. The CEX Family Interview files provide total expenditures and the amount spent on gasoline for each household during the 3 months prior to the CEX interview. For each household member, the Member Files include usual weekly work hours, occupation, the gross amount of last pay, the duration of the last pay period, and a variety of member income measures. The CEX is a rotating panel survey. Each quarter, 20% of the sample is rotated out and replaced by new consumer units. We pool observations for households across quarters.

We estimate two demand systems: one for one-adult households and the other for two-adult households with one adult male and one adult female (where an adult is at least 18 years of age).[21] Each adult's leisure is treated as a separate good. Thus, the two-adult demand system includes four goods: gasoline, male leisure, female leisure, and a composite of all other goods. The twelve quarters in the 1996 through 1998 Consumer Expenditure Surveys have 4659 one-adult households and 5047 two-adult households under 65 with complete records of the necessary variables. Each household appears in the data one to four times, giving a total of 9725 one-adult observations and 11034 two-adult observations. Females head 54% of the one-adult households. In one adult households, 78% of women and 83% of men work. In two-adult households, 71% of women and 88% of men work.

The CEX provides quarterly gasoline expenditure, which we divide by 13 to get weekly gas expenditure. To calculate weekly spending on other goods, we first convert the CEX's measure of quarterly total expenditures into weekly total expenditures. Then we subtract weekly gasoline expenditure from total weekly expenditures to obtain spending on all other goods.

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[20] Note that the use of any linear approximation to the price index in Eq. (19) implies that the symmetry restriction (19d) is also an approximation.

[21] We exclude households with adults over the age of 65. Less than 5% of those over 65 work, and thus non-labor income is very important for this group. We do not realistically model capital income, as discussed in Section 1. Thus, excluding those over 65 likely introduces much less error than would including this group.

To derive leisure “expenditure,” we set the weekly time endowment at 90 hours, which is the highest number of hours worked in the sample. Hours of leisure then equal 90 minus the number of hours worked.[22] To obtain the price of leisure (the wage) we first calculate the wage net of tax using state and federal effective tax rates from the NBER’s TAXSIM model.[23] Since we do not observe wages for individuals who do not work, we follow Heckman (1979) to correct for selectivity bias (see Appendix B for more detail). Weekly leisure expenditure then equals the selectivity-corrected net wage times the number of hours of leisure per week.

For gas prices and the price of other goods, we use the ACCRA cost-of-living index. This index compiles prices of many separate goods as well as overall price levels for approximately 300 cities in the United States. It is most widely used to compare the overall cost-of-living across cities. It also lists for each quarter the average prices of regular, unleaded, national-brand gasoline.[24] Since the CEX reports only the state of residence of each household, not the city, we average the city prices within each state to obtain a state gasoline price and price index for each calendar quarter.[25] Then we assign a gas price and a price index to each household based on state of residence and CEX quarter. For households whose CEX quarters overlap two quarters of price data, we use a weighted average of those two quarters. We use the ACCRA price index divided by 100 as the price of other goods, and calculate the price index (P^h) using Eq. (21).

Table 1 lists summary statistics for the demand system estimation sample (working households that consume gasoline). One-and two-adult households each spend about 2% of their income on gasoline. One-adult households spend a bit less than 50% of full income on leisure, as compared to roughly 55% for two-adult households. The average selectivity-corrected net wage is $8.31 per hour in the one-adult sample, and $11.02 per hour for men and $8.60 per hour for women in the two-adult sample.[26]

2.3. System estimation and results

To incorporate differences among households, the constant terms in Eq. (17) are assumed to depend on a vector of household and individual specific characteristics, c_r^h, and to include an error term, e_j^h, that represents unobserved differences in preferences:

$$\alpha_j^h = \zeta_{j0} + \sum_r \zeta_{jr} c_r^h + e_j^h, \qquad j = \text{gasoline, leisure, other goods} \tag{22}$$

where ζ_{j0} and the ζ_{jr}’s are parameters to be estimated.

Some households have zero gas expenditure. To correct for the selection bias that may arise, we estimate a probit on the choice of whether to consume gasoline and use the resulting inverse

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[22] Demand system estimates can be sensitive to the choice of time endowment. We therefore experimented with time endowments of 100 and 112 hours per week. In neither case do the results change significantly.

[23] These tax rate estimates should be reasonably accurate given the level of detail in the TAXSIM model, which incorporates state and federal tax brackets, the earned income tax credit, the child tax credit, deductibility of state income taxes, and other important features of the tax code. Some of these features, such as credit phase-outs, may cause the marginal tax rate to differ from the statutory marginal rate. Therefore, marginal tax rates are calculated based on a $1000 increase in earned income. For more detail on TAXSIM, see Feenberg and Coutts (1993). The tax rate estimates, however, do not include sales taxes or Social Security payroll taxes, and thus will understate the true tax rate. Thus, our results will tend to understate the importance of the cross-price elasticity with leisure.

[24] As a robustness check, we also replicated our analysis using gas price data from the U.S. Energy Information Administration’s *Petroleum Marketing Monthly* rather than from ACCRA. The results were essentially unchanged.

[25] Within-state variation in gas prices is small. For example, for the fourth quarter of 1997, the average within-state standard deviation is 4 cents. Cross-state and time-series standard deviations are each more than twice as large.

[26] The wage distribution in our sample closely follows the distribution in the 1997 Current Population Survey.

Table 1
Summary statistics for working households with non-zero gas consumption*

Variable	One-adult households		Two-adult households	
	Mean	Standard deviation	Mean	Standard deviation
Gasoline per week (gal)	13.78	10.97	24.67	16.07
One-adult hours per week	41.25	10.92	–	–
Two-adult male hours per week	–	–	44.76	10.34
Two-adult female hours per week	–	–	37.54	11.09
Gasoline share of expenditures	.02	.01	.02	.01
One-adult leisure share of expenditures	.49	.11	–	–
Two-adult male leisure share of expenditures	–	–	.29	.09
Two-adult female leisure share of expenditures	–	–	.26	.07
Other good share of expenditures	.50	.15	.44	.12
Gas price ($)	1.19	.12	1.19	.11
Other good price (index)	1.04	.10	1.04	.11
One-adult Heckman-corrected net wage ($)	8.31	2.36	–	–
Two-adult Male Heckman-corrected net wage ($)	–	–	11.02	3.26
Two-adult female Heckman-corrected net wage ($)	–	–	8.60	2.20
$\ln(y/P)$	5.72	.50	6.23	.45
One-adult age (years)	37.2	11.4	–	–
Two-adult male age (years)	–	–	38.5	10.0
Two-adult female age (years)	–	–	37.0	9.5
One-adult education: <high school diploma (%)	6.8	–	–	–
One-adult education: high school diploma (%)	23.3	–	–	–
One-adult education: >high school diploma (%)	69.9	–	–	–
Two-adult male education: <high school diploma (%)	–	–	8.5	–
Two-adult male education: high school diploma (%)	–	–	27.9	–
Two-adult male education: >high school diploma (%)	–	–	63.6	–
Two-adult female education: <high school diploma (%)	–	–	6.8	–
Two-adult female education: high school diploma (%)	–	–	26.9	–
Two-adult female education: >high school diploma (%)	–	–	66.4	–
Race of household head				
White (%)	82.6	–	87.5	–
Black (%)	13.7	–	8.8	–
Asian (%)	.7	–	.8	–
Other race (%)	3.0	–	2.9	–
Number of children	.41	.87	1.16	1.18
Region				
Northeast (%)	13.3	–	13.3	–
Midwest (%)	24.5	–	25.8	–
South (%)	34.1	–	35.5	–
West (%)	28.1	–	25.4	–
Observations	6553	–	7162	–

*Of the one-adult households 54% are headed by females.

Mills ratios (R_g^h) for gasoline (see Appendix B for more detail). Substituting Eq. (22) into Eq. (17) and adding R_g^h yield the following equations for estimation:

$$s_j^h = \zeta_{j0} + \sum_r \zeta_{jr} c_r^h + \sum_k \gamma_{jk} \log p_k^h + \beta_j \log(y^h/P^h) + \theta_j R_g^h + e_j^h. \tag{23}$$

We estimate the demand system defined by Eq. (23) using working households that consume gasoline, separately for one-adult and two-adult households. We impose the restrictions in Eq. (19a–d) and drop the equation for other goods. The vector c_r^h includes member and household characteristics that may affect gasoline or leisure shares: the members' age, age squared, race, sex (in one-adult estimation only), education, and number of children.[27] In addition, a wide range of local factors could affect gasoline use or work behavior—everything from availability of public transportation to local urban design to cultural differences. Because many of these factors are unmeasurable, we include state fixed effects to account for them. Finally, to account for seasonal variation in gas demand, we include fixed effects for the month of the CEX interview.

Under this approach, the own-price gas demand elasticity is identified based on cross- state differences in quarter-to-quarter gas price variation, because cross-state variation is picked up by the state fixed effects and month-to-month variation by the month fixed effects. The own- and cross-price labor supply elasticities are identified primarily by cross-section wage variation within each state.[28] This requires the implicit assumption that unobserved household characteristics are not correlated both with wages and with gas consumption or hours worked.

We use instrumental variables to control for potential endogeneity. The net wage may be endogenous for two reasons. First, the gross wage is determined by dividing earnings by hours of work, and both variables may be measured with error. Thus, hours worked and wage rates may be correlated. Second, the marginal income tax rate depends on income. We therefore instrument for the net wage rate with its occupation-, state-, and gender-specific mean.[29]

The real income term $\ln(y^h/P^h)$ may also be endogenous, because it is a function of individual-specific shares that are also dependent variables. We instrument for this term, using an alternative price index obtained by replacing the individual-specific shares in Eq. (21) with the sample mean shares.[30]

Finally, gas prices may be endogenous. For example, a local economic boom that increases hours worked could also drive up local gas prices. We examined the robustness of our results using two different instruments for state-level gasoline prices: national-average gas prices (from our data) and gasoline refinery outages (from Muehlegger, 2004). In each case, our main results were stronger with the instrument than without: gasoline was more complementary to leisure and the optimal gas tax rate was higher. But both instruments have potential problems.[31] Therefore, we report results based on estimation without any instrument for gas prices.[32]

Since the equations in Eq. (23) are functions of the same explanatory variables, error terms are likely correlated across equations. We therefore use three-stage least squares (3SLS), which lets us impose the cross-equation restrictions in Eq. (19a–d), control for endogeneity with

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[27] The probits used to correct for selectivity each include at least one variable not included in the demand system.

[28] It might therefore seem that we estimate long-run labor supply elasticities and short-run gas demand elasticties. But since the coefficients are jointly estimated, none of our elasticities is strictly short-run or long-run.

[29] Observations for workers in two occupation categories (farming, forestry, fishing, and groundskeeping is the first and the armed forces the second) are spread very thinly across states. For workers with these occupations, we instrument for net wage with the national mean net wages by occupation rather than the state level means.

[30] We also estimate our system using this alternative index instead of the index in Eq. (21). This does not noticeably affect any of the results, nor does running the demand system without any instruments at all.

[31] While the national-average gas price will be unaffected by local business cycles, it would be affected by national business cycles (though no substantive national macroeconomic fluctuations occurred during our sample period). And major refinery outages are rare, so using them as an instrument leads to much larger confidence intervals. We also cannot use state gas tax rates as an instrument, because there is essentially no within-state variation in these rates during our sample period, and all of the cross-state variation is absorbed by the state fixed effects.

[32] We also do not correct for the potential endogeneity of fuel efficiency in this estimation. West (2004) uses similar data to estimate demand for miles driven and finds that accounting for this endogeneity results in less elastic demand. The more inelastic is gas demand, the larger will be the effect of the cross-price elasticity with leisure on the optimal tax rate. Thus, correcting for this endogeneity would likely strengthen our findings.

Table 2
One-adult household demand system estimation results*

	Gas share	Leisure share
ln(gas price)	0.0038	−0.0047
	(0.0026)	(0.0017)
ln(other good price)	0.0009	−0.1071
	(0.0030)	(0.0163)
ln(net wage)	−0.0047	0.1119
	(0.0017)	(0.0165)
ln(y/P)	−0.0131	−0.1829
	(0.0008)	(0.0145)
Inverse mills ratio(gasoline)	−0.0150	0.4710
	(0.0018)	(0.0382)
Age	−0.0002	0.0014
	(0.0002)	(0.0027)
Age squared	0.000002	−0.000014
	(0.000002)	(0.000034)
Black	0.0018	−0.0824
	(0.0007)	(0.0140)
Asian	−0.0010	0.0306
	(0.0027)	(0.0407)
Other race	0.0003	−0.0483
	(0.0014)	(0.0241)
High school degree	−0.0059	0.1147
	(0.0014)	(0.0201)
More than high school degree	−0.0094	0.1619
	(0.0016)	(0.0222)
Female	−0.0041	0.0099
	(0.0007)	(0.0124)
Number of children	0.0014	−0.0158
	(0.0003)	(0.0041)
Constants	0.1336	1.2255
	(0.0075)	(0.1229)
Number of observations	6553	6553

*These are 3SLS regressions with ln(mean net wage by occupation, by state and gender) instruments for ln(net wage) and ln(y/P) calculated using the price index based on mean expenditure shares as instruments for ln(y/P) calculated using individual-specific shares. All regressions include state and month dummy variables. Bootstrapped standard errors are in parentheses.

instrumental variables, and account for the error correlation structure using generalized least squares.[33]

Tables 2 and 3 present the system estimation results along with standard errors based on 1500 replications of a nonparametric bootstrap. Each bootstrap replication recomputes the Heckman-corrected wage and the inverse Mills ratios from the discrete choice of whether to consume gasoline, as well as the regression coefficients. Thus, the standard error estimates incorporate variation in the estimated selectivity-corrected wages and inverse Mills ratios. Because

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[33] In principle, the full econometric model, including all discrete and continuous choices, might be estimated using maximum likelihood, but this would be difficult to implement. Since censoring occurs in both gasoline and leisure demand, and for either or both the male and female in two-adult households, we would need to evaluate multiple integrals in the likelihood function. Such a procedure would probably be too computationally intensive to be practical, particularly given that we need to bootstrap standard errors for our elasticity and optimal tax estimates.

Table 3
Two-adult household demand system estimation results*

	Gas share	Male leisure	Female leisure
ln(gas price)	0.0102	−0.0061	−0.0031
	(0.0018)	(0.0010)	(0.0009)
ln(other good price)	−0.0011	−0.0604	−0.0491
	(0.0020)	(0.0094)	(0.0075)
ln(male net wage)	−0.0061	0.1383	−0.0717
	(0.0010)	(0.0086)	(0.0052)
ln(female net wage)	−0.0031	−0.0717	0.1239
	(0.0009)	(0.0052)	(0.0069)
$\ln(y/P)$	−0.0090	−0.1687	−0.1694
	(0.0006)	(0.0067)	(0.0050)
Inverse mills ratio (gasoline)	−0.0168	0.1820	0.1653
	(0.0024)	(0.0269)	(0.0212)
Male age	0.0003	−0.0004	0.0006
	(0.0002)	(0.0016)	(0.0011)
Male age squared	−0.000003	0.000007	−0.000004
	(0.000002)	(0.000020)	(0.000014)
Black male	−0.0006	−0.0119	−0.0091
	(0.0015)	(0.0147)	(0.0127)
Asian male	−0.0011	0.0189	0.0012
	(0.0018)	(0.0149)	(0.0146)
Other race male	0.0002	−0.0243	0.0087
	(0.0014)	(0.0110)	(0.0100)
Male high school degree	−0.0020	0.0132	0.0035
	(0.0010)	(0.0064)	(0.0048)
Male more than high school degree	−0.0022	0.0192	0.0067
	(0.0011)	(0.0076)	(0.0052)
Female age	0.0005	0.0007	−0.0031
	(0.0002)	(0.0012)	(0.0013)
Female age squared	−0.000005	−0.000006	0.000042
	(0.000002)	(0.000016)	(0.000016)
Black female	0.0002	−0.0090	−0.0096
	(0.0016)	(0.0149)	(0.0132)
Asian female	0.0016	0.0037	−0.0218
	(0.0021)	(0.0237)	(0.0110)
Other race female	−0.0019	0.0235	−0.0124
	(0.0013)	(0.0103)	(0.0099)
Female high school degree	0.0004	−0.0044	0.0103
	(0.0009)	(0.0062)	(0.0060)
Female more than high school degree	0.0004	−0.0032	0.0205
	(0.0010)	(0.0067)	(0.0067)
Number of children	0.0004	−0.0019	0.0075
	(0.0002)	(0.0013)	(0.0010)
Constants	0.0904	1.3480	1.4282
	(0.0054)	(0.0565)	(0.0444)
Number of observations	7162	7162	7162

*3SLS regressions use ln(mean net wage by occupation, by state and gender) instruments for ln(net wage) and $\ln(y/P)$ calculated using the price index based on mean expenditure shares as instruments for $\ln(y/P)$ calculated using individual-specific shares. All regressions include state and month dummy variables. Bootstrapped standard errors are in parentheses.

Table 4
One-adult elasticities

	Gas price	Wage	Other good price
Compensated price elasticities			
Gasoline	−0.750	0.180	0.586
	(−1.095 −0.457)	(0.006 0.355)	(0.255 0.935)
Labor	−0.009	0.353	−0.296
	(−0.017 −0.001)	(0.261 0.459)	(−0.384 −0.217)
Other good	0.0163	0.203	−0.209
	(0.008 0.028)	(0.115 0.229)	(−0.242 −0.135)
Uncompensated price elasticities			
Gasoline	−0.771	0.305	0.455
	(−1.088 −0.479)	(0.131 0.474)	(0.084 1.094)
Labor	0.003	0.040	0.024
	(−0.005 0.011)	(−0.066 0.168)	(−0.074 0.128)
Other good	−0.005	0.621	−1.009
	(−0.014 0.005)	(0.356 0.665)	(−1.075 −0.947)

Bias-corrected 95% confidence intervals are in parentheses, based on 1500 replications of a nonparametric clustered bootstrap.

observations for the same household for multiple quarters are not independent, we cluster observations by household in generating each bootstrap sample.

Among one-adult households, gas share is higher for blacks, males, and those with less education, more children, or higher wages. Leisure share is lower for blacks and those with less education or more children. Higher wages or higher prices for other goods reduce leisure share, while higher gas prices increase it. The two-adult estimates generally mirror the one-adult estimates, though the magnitudes differ. The share of leisure (for either adult) increases as his or her wage increases and decreases as the wage of the other adult in the household increases.

Tables 4 and 5 present elasticities for the one-adult and two-adult samples, respectively, along with bias-corrected bootstrap confidence intervals. These elasticities are calculated separately for each household and then aggregated, rather than being calculated for a representative household.[34] Compensated own-price gas and other-good demand elasticities are negative, and compensated own-wage labor elasticities are positive.

Gasoline own-price elasticity estimates are roughly −0.75 for one-adult households and −0.27 for two-adult households. Aggregating these estimates yields an elasticity very similar to that found in recent work by Small and Van Dender (2005). For one-adult households, the compensated and uncompensated labor supply elasticities are 0.35 and 0.04, respectively. For two-adult households, compensated own-wage labor supply elasticities are 0.19 for men and 0.34 for women, while uncompensated elasticities are 0.06 and 0.24. These fall into the ranges reported in surveys by Fuchs et al. (1998) and Blundell and MaCurdy (1999).

The other important elasticity in Eq. (15) is the uncompensated cross-price elasticity of labor with respect to the price of gasoline. A positive value for this elasticity raises the optimal gas tax, because in this case an increase in the price of gas discourages leisure–which is overconsumed

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[34] In most cases, aggregate demand elasticities under the AIDS are equal to the elasticity for a representative household, but that property does not hold when some households are at a corner solution, as is the case here. Thus, it is necessary to aggregate individual household elasticities. Appendix A provides equations for the household demand elasticities in terms of the estimated parameters and for elasticity aggregation.

Table 5
Two-adult elasticities

	Gas price	Male wage	Female wage	Other good price
Compensated price elasticities				
Gasoline	−0.269	−0.123	0.042	0.354
	(−0.538 −0.011)	(−0.269 0.003)	(−0.051 0.140)	(0.061 0.639)
Male labor	0.007	0.187	0.012	−0.181
	(0.000 0.015)	(0.105 0.272)	(−0.018 0.042)	(−0.256 −0.096)
Female labor	−0.005	0.028	0.337	−0.321
	(−0.016 0.005)	(−0.030 0.087)	(0.252 0.427)	(−0.415 −0.241)
Other good	0.012	0.102	0.095	−0.201
	(0.002 0.021)	(0.048 0.141)	(0.070 0.123)	(−0.255 −0.134)
Uncompensated price elasticities				
Gasoline	−0.283	0.011	0.110	0.178
	(−0.540 −0.021)	(−0.133 0.134)	(0.020 0.213)	(−0.285 0.646)
Male labor	0.013	0.062	−0.049	−0.045
	(0.006 0.022)	(−0.019 0.152)	(−0.080 −0.019)	(−0.126 0.043)
Female labor	0.002	−0.113	0.242	−0.165
	(−0.008 0.013)	(−0.174 −0.055)	(0.158 0.329)	(−0.252 −0.076)
Other good	−0.016	0.548	0.328	−1.090
	(−0.026 −0.007)	(0.314 0.588)	(0.295 0.362)	(−1.154 −1.003)

Bias-corrected 95% confidence intervals are in parentheses, based on 1500 replications of a nonparametric clustered bootstrap.

because it is untaxed–thus yielding a welfare gain. A negative value reverses this effect, lowering the optimal tax. The prior literature on optimal environmental taxes has implicitly assumed that this elasticity is slightly negative, as a result of assuming separability and homogeneity. In contrast, we find a positive elasticity for one-adult households and for both genders in two-adult households, which implies a higher optimal gas tax rate than that suggested by prior work–though the elasticity is significant only for men in two-adult households.[35]

One possible explanation for this result is that a higher gas price leads to a reduction in leisure driving that is substantially greater than the reduction in work-related driving (primarily commuting). Parry and Small (2005) note that commuting makes up less than half of all vehicle miles traveled in the US, and it is reasonable to think that the demand for leisure driving would be more elastic than the demand for work-related driving.[36] A more sophisticated argument is

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[35] This result is sensitive to the inclusion of state fixed effects: dropping the state fixed effects switches the sign on the elasticity of labor supply with respect to the gas price from positive (meaning gas and leisure are complements) to negative (gas and leisure are substitutes). But this sensitivity is hardly surprising, given the importance of unobserved state-level variables; joint significance tests overwhelmingly reject dropping state fixed effects. In contrast, dropping month fixed effects has little effect on the results. Because estimates from 3SLS estimation are often very sensitive to specification error, we also estimated the system using two-stage least squares (2SLS). Estimates using 2SLS with and without fixed effects closely follow those from the same specifications using 3SLS.

[36] The demand for work-related driving might well be more elastic in the long run, as households could move closer to work. But such moves would not affect the cross-price elasticity with leisure, which depends on how gas price changes affect the number of trips to work, not on how they affect the length of those trips. Unfortunately, we cannot test hypotheses about leisure-related vs. work-related driving, because our data do not distinguish the two. We assume that the government also cannot distinguish these two, and thus cannot tax them differently. If it could, then differences in cross-price effects on labor supply would suggest that gas used for work-related driving should be taxed at a lower rate than gas used for leisure driving. But differences in marginal damage act in the opposite direction, since the congestion externality is larger for work-related driving (because it is more likely to occur during peak travel times). Thus, it is unclear which type of driving should face the higher tax rate.

Table 6
Estimated optimal tax rates (in 1997 dollars)

	MED	MCPF	Optimal tax rate
(One-adult households only)			
Fixed labor supply	\$0.77	1	\$0.77
Labor supply not fixed (utility separable and homothetic)	\$0.77	1.01	\$0.76
		(0.99 1.03)	(\$0.74 \$0.78)
Labor supply not fixed (utility separable, nonhomothetic)	\$0.77	1.01	\$0.87
		(0.99 1.03)	(\$0.83 \$0.92)
Labor supply not fixed (utility nonseparable, nonhomothetic)	\$0.77	1.01	\$0.82
		(0.99 1.03)	(\$0.73 \$0.95)
(Two-adult households only)			
Fixed labor supply	\$0.77	1	\$0.77
Labor supply not fixed (utility separable and homothetic)	\$0.77	1.03	\$0.75
		(1.00 1.05)	(\$0.73 \$0.77)
Labor supply not fixed (utility separable, nonhomothetic)	\$0.77	1.03	\$10.1
		(1.00 1.05)	(\$0.66 \$3.30)
Labor supply not fixed (utility nonseparable, nonhomothetic)	\$0.77	1.03	\$1.30
		(1.00 1.05)	(\$0.82 \$5.34)
(All households)			
Fixed labor supply	\$0.77	1	\$0.77
Labor supply not fixed (utility separable and homothetic)	\$0.77	1.02	\$0.75
		(1.00 1.04)	(\$0.74 \$0.77)
Labor supply not fixed (utility separable, nonhomothetic)	\$0.77	1.02	\$0.93
		(1.00 1.04)	(\$0.84 \$1.18)
Labor supply not fixed (utility nonseparable, nonhomothetic)	\$0.77	1.02	\$1.04
		(1.00 1.04)	(\$0.87 \$1.48)

All monetary values are in 1997 dollars. Bias-corrected 95% confidence intervals are in parentheses, based on 1500 replications of a nonparametric clustered bootstrap. Marginal external damage (MED) includes congestion and accident damages as well as environmental damages. MED estimates are taken from Parry and Small (2005) and deflated from 2000 to 1997 dollars.

that driving is a relatively time-intensive activity (at the margin, once households have incurred the fixed cost of buying a car). Becker's (1965) model of time use suggests that time-intensive goods are complements to leisure (or, more precisely, to non-market time).

3. Optimal tax calculations

This section calculates the optimal gasoline tax rate and compares it to the optimal rates implied by each of the sets of assumptions used in prior work: fixed labor supply, homotheticity and separability of leisure, or just separability. We present these estimates in Table 6.

Our data set provides values for most of the variables in the formulas for the optimal tax rate (15) and the MCPF (14), while the estimates from the previous section allow us to calculate the necessary derivatives of demand.[37] The only additional parameter value needed is for marginal

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[37] We assume that the derivatives of demand at the optimum are the same as those in the status quo. In addition, Eq. (15) depends on the total derivative of gas demand, which includes the effects of both gas tax and income tax changes. But this derivative is very close to the compensated derivative, and thus we use that value. Finally, for consistency with Section 1, where the externality came from consumption of a final good, we assume that the tax is imposed only on consumer use of gasoline, not on gas used as an intermediate good. This seems reasonable, since Parry and Small (2005) note that intermediate use of gasoline is only a very small share of the total.

external damage. We take this value from Parry and Small (2005), who estimate marginal damages at 83 cents per gal in year 2000 dollars, a figure that incorporates pollution, congestion and accident externalities. To make this number consistent with the rest of our data, we use the CPI to deflate it, yielding an estimate of 77 cents in 1997 dollars.[38]

If labor supply were fixed, then the optimal tax would simply equal marginal damage. But allowing labor supply to vary leads to efficiency effects in the labor market, as well as in the gas market. We first consider the case in which utility is homothetic and leisure is separable in the utility function. In the absence of an externality, this implies that the optimal gas tax is zero.[39] With an externality, the optimal tax equals marginal damage divided by the MCPF.

Substituting the appropriate values into Eq. (14) yields estimates for the MCPF of 1.01 in the one-adult sample, 1.03 in the two-adult sample, and 1.02 in the full sample. These estimates are somewhat lower than those from the prior literature. This difference arises primarily because our estimates of uncompensated labor supply elasticities are lower than the prior literature assumes.[40] These MCPF estimates then imply that the optimal tax in the homothetic and separable case equals \$0.76 per gal. for the one-adult sample, \$0.75 for the two-adult sample, and \$0.75 for the full sample.

Relaxing the assumption of homotheticity but keeping separability gives a somewhat higher optimal gas tax–the same result noted by Parry and Small (2005). Substituting Eq. (16) and the appropriate parameter values into Eq. (15) yields an optimal tax of \$0.87 for the one-adult sample, \$1.01 for the two-adult sample, and \$0.93 for the full sample–all significantly above marginal damages. Because gasoline is a necessity, Eq. (16) implies that it is a relative leisure complement, which in turn implies a higher optimal tax rate.

Relaxing both separability and homotheticity gives the optimal tax formula from Eq. (15). Substituting in the appropriate parameter estimates yields an optimal gas tax rate of \$0.82 for the one-adult sample, \$1.30 for the two-adult sample, and \$1.04 per gal for the full sample. As is shown in Table 6, the confidence intervals around these rates are relatively wide. Nonetheless, the differences between the optimal rates and marginal damages are statistically significant at the 95% level for both the two-adult sample and the full sample, as are the differences between these rates and the optimal rates assuming both separability and homotheticity. The difference from the optimal tax assuming only separability is significant at the 90% level. Our estimates suggest that gas is not just a weaker substitute for leisure than are other goods, but that it is actually a complement to leisure: increasing the gas tax will increase labor supply (even ignoring the effects of the income tax cut financed by that gas tax increase). As a result, the optimal tax is substantially higher than it would be if gas were an average substitute for leisure.

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[38] We assume that marginal damage remains constant as the gas tax rate changes. It seems clear how certain elements of marginal damage would change (e.g., a higher gas tax will discourage driving, and thus will reduce the marginal external congestion cost). But whether marginal damage would rise or fall overall is far less clear.

[39] These assumptions imply uniform optimal commodity taxes. And under our tax normalization, a uniform commodity tax is represented by the income tax.

[40] For comparison, two recent studies of second-best optimal environmental taxation, Goulder et al. (1999) and Parry et al. (1999), each assume an uncompensated labor supply elasticity of 0.15 and a tax rate of 40%, which together imply an MCPF of 1.11. For our sample, assuming higher values for the uncompensated labor supply elasticities (0.15 for the one-adult sample and for men in the two-adult sample, and 0.3 for women in the two-adult sample) would imply a substantially higher MCPF and optimal gas tax. In the full sample, for example, this change implies an MCPF of 1.39 and an optimal gas tax rate (assuming neither separability nor homotheticity) of \$1.58.

The difference between the optimal tax and marginal damage–27 cents per gal (35% of marginal damage) for the full sample–is not enormous, but is quite important. And this difference has the opposite sign from what the prior literature on second-best optimal environmental taxation suggests. That literature certainly notes the theoretical possibility that the optimal tax may exceed marginal damage, for exactly the reasons found here, but gives no clear indication of how likely such an outcome might be or of how large the difference would be.

These results show that the separability and homotheticity assumptions (which are common in the second-best environmental tax literature) can be very important. Relaxing these estimates leads to a 29-cent increase (from \$0.75 to \$1.04) in the optimal tax. This is more than ten times the difference between marginal damage and the optimal tax rate with separability and homotheticity (\$0.77 vs. \$0.75)–which has been the major focus of this literature.

Even if there were no negative externalities associated with gasoline (i.e., if marginal damage were zero), the optimal tax rate would still equal \$0.28 (33% of the average pre-tax price in our sample). This implies the existence of a "double dividend" (a welfare increase even when externalities are ignored) from raising the gas tax above zero, but not from raising it above the average rate in our sample (\$0.34).[41] However, the 95% confidence interval for the optimal tax in this case runs from \$0.11 to \$0.72, so we cannot reject the hypothesis that raising the gas tax would yield a double dividend–or, to put it differently, that the optimal gas tax would exceed the average rate in our sample even if there were no externalities associated with gasoline use.

In this no-externality case, slightly less than half of the optimal tax (\$0.11, which is 13% of the average pre-tax price) is due to nonseparability. Thus, a study that assumes separability (as does nearly all prior empirical work on optimal taxes) would find an "optimal" tax rate that is only just over half of the correct value–a substantial underestimate.[42]

4. Conclusions

This paper estimates a complete consumer demand system without imposing separability or homotheticity, and applies those estimates together with a simple theoretical model to calculate the optimal tax on gasoline. We find that even if there were no negative externalities associated with gas use, the optimal gas tax would still be roughly 33% of the pre-tax price of gasoline, almost equal to the average tax rate in our sample. This is more than one-and-a-half times the "optimal" rate that would be implied if one were to assume that leisure is separable in utility, as nearly all prior studies have assumed. When we include externalities, we find that the optimal tax substantially exceeds marginal damage, contrary to results from the prior literature, which suggest that optimal environmental taxes are typically less than marginal damage.

Thus, our results clearly illustrate the importance of explicitly estimating cross-price elasticities with leisure rather than imposing restrictive assumptions in order to determine those

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[41] It is well-known that a tax reform that moves one tax closer to its optimal rate does not necessarily yield a welfare gain (e.g., see Dixit, 1975). But that result doesn't apply here: because our model includes only two consumption goods, such a reform will always yield a welfare gain.

[42] All of these calculations ignore equity considerations. Including such considerations would lower the estimated optimal tax rates, because the gas tax is regressive. But the optimal tax rate assuming separability would fall by the same amount as the optimal tax without separability, and thus the difference between the two would be unchanged.

elasticities.[43] This has important implications both for environmental regulation and for commodity taxation.

One obvious implication is that the efficiency gain from increasing the gas tax would be even larger than a first-best analysis would indicate. But the practical relevance of any result on optimal gasoline taxes may be limited by political constraints; the existing tax in the U.S. is far below what almost any economic analysis would indicate as the optimum. European gas tax rates are substantially above our estimated optimal tax rates, though Parry and Small (2005) notes that marginal external damage is higher in Europe, so the optimal tax in Europe is probably higher than our estimated optimal tax for the U.S.

Some readers may be tempted to use our results to support setting other environmental taxes at levels above marginal damages. This conclusion does not necessarily follow, given that other polluting goods are used for very different purposes than is gasoline. But our result does show that the case in which tax-interaction effects cause the optimal tax to exceed marginal damages is relevant in practice, not merely a theoretical possibility. This indicates far more uncertainty about the influence of second-best effects on environmental policy than prior work has suggested, and it shows that the widely used separability and homotheticity assumptions are not merely convenient simplifications; they can have large effects on the results. Similarly, results from the prior literature on commodity taxation should be interpreted with caution, because they rely on the assumption that leisure is separable in utility, which we have shown can substantially affect estimates of optimal tax rates.

Perhaps most importantly, our results suggest that future research–either on commodity taxation, environmental regulation, or in any of the other settings in which cross-price effects with leisure have been shown to affect optimal policy–needs to explicitly estimate those cross-price effects in order to yield accurate estimates of optimal policy.

Appendix A. Derivations and elasticity formulas

A.1. Derivation of Eq. (14)

It is useful first to find expressions for how τ_L and T change for a change in τ_Y. Taking a total derivative of Eq. (9) with respect to τ_Y and substituting in Eqs. (5) and (6) yield

$$\frac{\mathrm{d}\tau_L^{hi}}{\mathrm{d}\tau_Y} = \frac{w^{hi}}{1-\tau_Y} \text{ and } \frac{\mathrm{d}T^h}{\mathrm{d}\tau_Y} = \frac{I^h}{1-\tau_Y}. \tag{A1}$$

To derive an expression for the aggregate change in utility from a change in τ_Y, take the total derivative of utility (1) with respect to τ_Y, sum over households, substitute in the first-order conditions (10) and a total derivative of the consumer budget constraint (3) with respect to τ_Y, and rearrange terms. Note that the definition of the MCPF in Eq. (14) includes only effects in the labor market, so we ignore the externality term in Eq. (1). This gives

$$\sum_h \frac{1}{\lambda^h}\frac{\mathrm{d}U^h}{\mathrm{d}\tau_Y} = -\sum_h \left[\frac{\mathrm{d}T^h}{\mathrm{d}\tau_Y} + \sum_i L^{hi}\frac{\mathrm{d}\tau_L^{hi}}{\mathrm{d}\tau_Y}\right]. \tag{A2}$$

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[43] One potential exception would be a tax or regulation affecting an intermediate good used to produce a wide range of consumer goods. In that case, it might well be reasonable to assume average substitutability with leisure.

To derive an expression for the change in government revenue from a change in τ_Y, take the total derivative of the left-hand side of the government budget constraint (8) with respect to τ_Y and rearrange terms. Again, Eq. (14) includes only effects in the labor market, so we ignore the revenue from the tax on the polluting good. This gives

$$\mathrm{d}\sum_h\left[\sum_i \tau_L^{hi}L^{hi}+T^h\right]\Big/\mathrm{d}\tau_Y$$
$$=\sum_h\left[\frac{\mathrm{d}T^h}{\mathrm{d}\tau_Y}+\sum_i\left(L^{hi}\frac{\mathrm{d}\tau_L^{hi}}{\mathrm{d}\tau_Y}+\tau_L^{hi}\frac{\partial l^{hi}}{\partial I^h}\frac{\mathrm{d}T^h}{\mathrm{d}\tau_Y}+\sum_j\tau_L^{hi}\frac{\partial l^{hi}}{\partial w^{hj}}\frac{\mathrm{d}\tau_L^{hj}}{\mathrm{d}\tau_Y}\right)\right]. \tag{A3}$$

Dividing Eq. (A2) by Eq. (A3) and then substituting in Eqs. (A1) and (3) give Eq. (14).

A.2. Rewriting Eq. (12) in terms of the MCPF

The total derivative $\frac{\mathrm{d}l^i}{\mathrm{d}\tau_D}$ depends on how the income tax adjusts to hold government revenue constant. Taking a total derivative of the government budget constraint (8), substituting in Eq. (A1) and the equation for the MCPF (14) and rearranging yield

$$\frac{\mathrm{d}\tau_Y}{\mathrm{d}\tau_D}=-(1-\tau_Y)\eta\sum_h\left[D^h+\tau_D\frac{\mathrm{d}D^h}{\mathrm{d}\tau_D}-\sum_i\tau_L^{hi}\frac{\partial l^{hi}}{\partial p_D^h}\right]\Bigg/\sum_h Y^h. \tag{A4}$$

Substituting together $\frac{\mathrm{d}l^{hi}}{\mathrm{d}\tau_D}=\frac{\partial l^{hi}}{\partial p_D^h}-\frac{\partial l^{hi}}{\partial w^{hi}}\frac{\mathrm{d}\tau_L^{hi}}{\mathrm{d}\tau_Y}\frac{\mathrm{d}\tau_Y}{\mathrm{d}\tau_D}-\frac{\partial l^{hi}}{\partial I^h}\frac{\mathrm{d}T^h}{\mathrm{d}\tau_Y}\frac{\mathrm{d}\tau_Y}{\mathrm{d}\tau_D}$ and Eqs. (A1) and (A4) yields

$$\sum_h\sum_i\tau_L^{hi}\frac{\mathrm{d}l^{hi}}{\mathrm{d}\tau_D}=-\sum_h\left[(\eta-1)\left(D^h+\tau_D\frac{\mathrm{d}D^h}{\mathrm{d}\tau_D}\right)-\eta\sum_i\tau_L^{hi}\frac{\partial l^{hi}}{\partial p_D^h}\right]. \tag{A5}$$

Substituting this equation into Eq. (12) and canceling terms give

$$\sum_h\frac{1}{\lambda^h}\frac{\mathrm{d}U^h}{\mathrm{d}\tau_D}=\sum_h\left[(\eta\tau_D-\theta)\frac{\mathrm{d}D^h}{\mathrm{d}\tau_D}+(\eta-1)D^h-\eta\sum_i\tau_L^{hi}\frac{\partial l^{hi}}{\partial p_D^h}\right]. \tag{A6}$$

A.3. Demand derivatives in terms of estimated parameters

The demand system used in this paper does not directly yield estimates of derivatives or elasticities of demand; instead, these derivatives and elasticities are functions of the estimated parameters. Taking a derivative of the AIDS budget share Eq. (17) with respect to p_i^h gives

$$\frac{\partial s_j^h}{\partial p_i^h}=\frac{\gamma_{ji}}{p_i^h}-\beta_j\frac{\partial(\log P^h)}{\partial p_i^h}. \tag{A7}$$

Taking a similar derivative of the price index (21) yields

$$\frac{\partial(\log P^h)}{\partial p_i^h} = \frac{s_i^h}{p_i^h} + \sum_k \log(p_k^h/\overline{p}_k)\frac{\partial s_k^h}{\partial p_i^h}. \tag{A8}$$

Solving Eqs. (A7) and (A8) for $\frac{\partial s_j^h}{\partial p_i^h}$ and then converting the share into a quantity yields an expression for the uncompensated derivative of demand for good i with respect to the price of good j (where j is any good except leisure):

$$\frac{\partial q_j^h}{\partial p_i^h} = \frac{y^h}{p_i^h p_j^h}\left[\gamma_{ji} - \beta_j \frac{s_i^h + \sum_k \gamma_{ki}\log(p_k^h/\overline{p}_k)}{1 + \sum_k \beta_k \log(p_k^h/\overline{p}_k)}\right] - \frac{q_j^h}{p_i^h} d_{ij}, \tag{A9}$$

where q_j^h is the quantity of good j consumed and d_{ij} is the Kronecker delta, equal to 1 if $i=j$ and zero otherwise.

A similar process for a change in income gives

$$\frac{\partial q_j^h}{\partial y^h} = \frac{1}{p_j^h}\left[\frac{\beta_j}{1 + \sum_k \beta_k \log(p_k^h/\overline{p}_k)}\right] + \frac{q_j^h}{y^h}. \tag{A10}$$

It is then straightforward to use the Slutsky equation to obtain the compensated derivative of demand for good i with respect to the price of good j, which is given by

$$\frac{\partial q_{jC}^h}{\partial p_i^h} = \frac{y^h}{p_i^h p_j^h}\left[\gamma_{ji} - \beta_j \frac{\sum_k \gamma_{ki}\log(p_k^h/\overline{p}_k)}{1 + \sum_k \beta_k \log(p_k^h/\overline{p}_k)}\right] + \frac{q_i^h q_j^h}{y^h} - \frac{q_j^h}{p_i^h} d_{ij}, \tag{A11}$$

where the subscript C denotes a compensated derivative.

A.4. Correcting derivatives for corner solutions

The expressions in Eqs. (A9), (A10), and (A11) are valid for a household that is at an interior solution, but not for those at corner solutions (i.e., those households who don't consume gasoline, or where one or both adults do not work). The parameter estimates should still be valid for these households (because of the corrections for selectivity described in Appendix B), but the expressions for derivatives in terms of the estimated parameters will differ. We follow the standard "virtual price" approach, recognizing that a household at a corner will have a shadow price for the good that it is not consuming (or, in the case of leisure, that it is consuming its entire endowment of) that differs from the true price, as a result of the constraint imposed by the corner. This implies that if a household is constrained in its consumption of good k then

$$\frac{\partial \hat{q}_{jC}^h}{\partial p_i^h} = \frac{\partial q_{jC}^h}{\partial p_i^h} - \frac{\partial q_{jC}^h}{\partial p_k^h}\left(\frac{\partial q_{kC}^h}{\partial p_i^h} \bigg/ \frac{\partial q_{kC}^h}{\partial p_k^h}\right), \tag{A12}$$

where the “hat” denotes the derivative after correcting for the corner solution. Similarly,

$$\frac{\partial \hat{q}^h_{jC}}{\partial y^h} = \frac{\partial q^h_{jC}}{\partial y^h} - \frac{\partial q^h_{jC}}{\partial p^h_k}\left(\frac{\partial q^h_{kC}}{\partial y^h}\bigg/\frac{\partial q^h_{kC}}{\partial p^h_k}\right). \tag{A13}$$

Because consumption of good k is constrained, derivatives of demand for good k, or with respect to the price of good k will equal zero.[44] It is then straightforward to apply the Slutsky equation to obtain uncompensated derivatives (recognizing that the income effect for leisure will differ, because the household starts with an endowment of leisure).

A.5. Aggregating elasticities

We report aggregate elasticities in Tables 4 and 5 to clarify what is driving the optimal tax results. Thus, it is necessary to aggregate individual household demand derivatives to obtain aggregate elasticities. In doing this, we calculate the elasticity for a case in which each household faces the same absolute change in price.[45] This implies that the aggregate demand elasticity is given by

$$\varepsilon_{ji} = \overline{p}_i \sum_h \frac{\partial q^h_j}{\partial p^h_i}\bigg/\sum_h q^h_j, \tag{A14}$$

where

$$\overline{p}_i = \sum_h p^h_i q^h_i \bigg/ \sum_h q^h_i \tag{A15}$$

(note that this is the same average price that is used in computing the price index in Eq. (21). The equations for aggregate labor supply elasticities differ slightly, in that the quantities in Eqs. (A14) and (A15) are replaced with the amount of labor supplied.

Appendix B. Correcting for selectivity bias

This section explains corrections made for potential selection into work and into gasoline consumption. Results for the estimation discussed here are available from the authors by request.

B.1. The work decision

Since we do not observe wages for non-workers, we follow Heckman (1979) to correct for the associated selectivity bias. To do this, we estimate an equation for the choice of whether or not to work jointly with an equation for the net wage, using full-information maximum likelihood. We then use the results of this estimation to obtain estimated selectivity-corrected net wages.

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[44] If a household is at a corner solution for two goods, then this approach can be applied sequentially for the two goods.

[45] The reported elasticities are obviously somewhat sensitive to this assumption–because households initially face different prices, an equal-percentage change in price would give a slightly different result–and it is not entirely clear which assumption would be more appropriate. Fortunately, this has no effect on the optimal tax results, because the optimal tax formula in Eq. (15) is calculated using individual household demand derivatives, not aggregates.

We estimate selection models separately for the one-adult and two-adult sample, and separately for men and for women within each sample. The one-adult selection equation includes age, age squared, education, race, marital status, number of children, region, log of gas price, log of other good price, and state-specific quarterly unemployment rates.[46] The two-adult selection equation includes those variables plus partner's earnings and partner's demographic information.

Because of the linear approximation to the price index (21), wages affect the price derivatives of demand even for non-workers (though this effect is minimal), and thus we need predicted wages for non-workers. Because occupation is an important determinant of net wage but is observed only for workers, we run two selection models for each subsample, one to estimate workers' net wages and the other to estimate nonworkers' net wages. Within each subsample (where one such subsample, for example, is composed of women from one-adult households) both the selection models use the same set of observations of workers and nonworkers and identical selection equations. But the wage equations differ. To estimate net wages for nonworkers we specify a wage equation that includes education, age, age squared, race, marital status, region, and the inverse Mills ratio from the probits. To estimate net wages for workers, we include those same variables plus occupation indicators. Since the wage distribution is approximately log-normal, we define the dependent variable as the log of net wage.

These equations would be identified even if the variables in the selection equation were the same as those in the wage equation, but in that case, the identification would depend on the normality assumption. Note, however, that in our specification, the selection equations include number of children, the log of gas price, the log of the other good price, state-specific quarterly unemployment rates, and, in the case of two-adult households, partner's earnings; the wage equations do not. Number of children affects the fixed cost of working and thus the participation decision, but should not directly affect the wage; this is a standard exclusion restriction in the labor supply literature. Our demand system allows gas and other good prices to affect the continuous demand for leisure and thus it is reasonable to assume that they also affect the discrete work choice. While high price regions may also be high wage regions, there is no reason to postulate that an individual facing a high gas price or other good price will have a higher wage, since we control for region in our wage equation. Unemployment rates proxy for job availability in a state and thus affect the likelihood of working, but it is not clear why they would affect wages. Partner's earnings proxy for an individual's non-wage income, but should not directly affect an individual's wage; this is another standard exclusion restriction.

B.2. The gasoline decision

Another selection bias may arise because we exclude households that do not consume gasoline from the system estimation. To correct for this potential bias, we follow an approach analogous to the two-step version of the Heckman correction: we run probits on the dichotomous choice to consume or not consume gasoline, calculate the inverse Mills ratio for each household, and include that Mills ratio in each of the equations in the demand system estimation. We run separate probits for one-adult and two-adult households. Each probit includes the log of total goods expenditures, age, age squared, race, marital status, the number

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[46] Unemployment rates are gathered from the Bureau of Labor Statistics at www.bls.gov.

of children, region, an indicator for whether the household owns its house, and the logs of gas price and other good price. Demographic variables for both adults are included in the two-adult probit. Home ownership acts as a proxy for access to credit and thus increases the likelihood of owning an automobile and the likelihood of consuming gasoline (see West, 2004). We do not expect it to affect the continuous choice of gasoline and therefore we use this as an exclusion restriction.

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