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Optimal Income Taxation with Unemployment and Wage Responses: A Sufficient Statistics Approach†

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We derive a sufficient statistics tax formula in a model that incorporates unemployment and endogenous wages to study the shape of the optimal income tax. Key sufficient statistics are the macro employment response to taxation, the micro and macro participation response to taxation, and the wage-moderating effect of tax progressivity. We empirically implement the tax formula by estimating the micro and macro elasticities using policy variation from the United States. Our results suggest that the optimal tax more closely resembles a negative income tax than an earned income tax credit relative to the case where unemployment and wage responses are ignored. (*JEL* E24, H21, H23, H24, H31, J22, J31)

A large literature has sought to characterize the optimal income tax when there is a desire for redistribution (Mirrlees 1971, Diamond 1998, Saez 2001). Many of the papers in this literature typically assume that wages are exogenous and there is full employment. The objective of this paper is to theoretically and empirically investigate the optimal income tax in the presence of endogenous wages and involuntary unemployment.

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On the theory side, we build on the discrete model of Saez (2002). Individuals choose an "occupation" corresponding to a specific pretax income level (hereafter "wage") and tax liability. The model includes nonparticipation as an outside option and thus allows for selection into and out of the labor force. Saez interprets nonparticipation as unemployment. According to this definition, all unemployment is voluntary. We extend his model by introducing endogenous wages and involuntary unemployment, where some participants fail in their search to find a job. Gross wages and employment probabilities are assumed to be endogenous to the tax policy, and this endogeneity is captured by very flexible reduced-form functions. We do not impose any a priori restrictions on these reduced-form functions and thus are able to capture a broad set of microfoundations of the labor market with general equilibrium effects. Therefore, we adopt a "sufficient statistics" approach to characterizing the optimal income tax policy (Chetty 2009).

The first contribution of this paper is to derive a sufficient statistics optimal tax formula that is valid in the presence of endogenous wages and (involuntary) unemployment. Our formula generalizes the formula in Saez (2002) that includes both extensive and intensive labor supply responses.[1] It is expressed in terms of social welfare weights, the income distribution, *macroeconomic employment* responses to taxation, and *microeconomic* and *macroeconomic participation* responses to taxation.[2] By "micro" responses, we refer to responses to taxation holding wages and the unemployment rate in all occupations constant. "Macro" responses, on the other hand, allow both wages and unemployment rates to adjust to a change in taxes.

There are two main differences between our optimal tax formula and the one in Saez (2002). First, optimal tax formulas take into account the revenue effects of a tax reform. The revenue effects include both the mechanical change in tax revenue holding constant employment as well as behavioral responses due to incentive effects. In Saez (2002), behavioral responses are captured by labor supply responses, which are the same as micro employment responses due to the full employment and fixed wage assumptions. By contrast, in our model, labor supply responses are not sufficient to characterize revenue effects, since taxes affect equilibrium wages and unemployment through movements along the labor demand curve or search frictions. This drives a wedge between labor supply and employment responses and, as a result, behavioral responses are captured by macro employment responses to taxation, which are the sum of the direct labor supply effect plus any indirect effects on employment operating through spillovers.

Second, optimal tax formulas take into account how taxation affects the social objective. In Saez (2002), this is pinned down by the mechanical effect of taxes on consumption. This is for two reasons. First, the analysis is partial equilibrium, and taxes are assumed to affect only individual taxpayers (as opposed to firms). Second, labor supply responses have only second-order effects on the social objective due to the envelope theorem. Intuitively, labor supply responses due to a small change in

[1] This is equation (11) in the appendix of Saez (2002), which corresponds to the general case.

[2] For ease of exposition, we hereafter refer to microeconomic as "micro" and macroeconomic as "macro." Participation responses refer to changes in participation rates (i.e., the fraction of participants, employed or unemployed, in a given population) in response to tax reforms, while employment responses refer to changes in employment rates (i.e., the fraction of employed in a given population) in response to tax reforms.

taxes have no first-order effect on individuals' expected utility at an optimum; since individual utility is unaffected, social welfare is unaffected. In our model, taxes additionally affect wages and unemployment through spillover effects that operate in the market. These spillover effects have a direct impact on expected utilities, beyond the mechanical consumption effect, as they affect both gross wages (and hence consumption) and the probability of being employed.

We use a simple insight to characterize the social welfare effect in terms of sufficient statistics. We note that a tax reform alters the expected utility of participation in one occupation relative to nonparticipation. As a result, the magnitude of the participation response (in some occupation) to a given tax reform is informative about the magnitude of the utility change (in that occupation) generated by the tax reform. A tax cut that triggers a large increase in participation reveals that individuals experienced a large increase in expected utility. We use this intuition to show that when the social objective depends on individuals' expected utilities, the mechanical social welfare effects need to be inflated by the (matrix) ratio between macro and micro participation responses. This is because both the social objective and participation decisions depend on taxation only through the effect of taxes on expected utility.

We then apply our formula to investigate whether the existence of unemployment and the endogeneity of wages reinforce or lessen the desirability of an earned income tax credit policy (a larger transfer to the working poor than to the nonemployed; hereafter EITC) relative to a negative income tax policy (i.e., a larger transfer to the nonemployed than to the working poor; hereafter NIT).[3] For this purpose, we consider two special cases of the general model.

The first special case we consider assumes that the tax liability in a given occupation does not affect gross wages or conditional employment probabilities in other occupations. It also assumes that labor supply responses are concentrated along the extensive margin so that individuals can participate in only a single occupation or not participate at all. This is what we refer to as the "no-cross-effect" case. In this case, the optimal tax formula has a simple form that can be directly compared with the optimal tax formula in the pure extensive margin models of Diamond (1980), Saez (2002), and Choné and Laroque (2005, 2011). In particular, an EITC is desirable whenever the welfare weight on the working poor is larger than the ratio of the micro to the macro participation elasticities, while the threshold is one with fixed wages and full employment.

The second special case we consider assumes that gross wages and conditional employment probabilities in a given occupation depend on the tax liability in that occupation, the tax liabilities in two adjacent occupations, and the welfare benefit. Participation in a given occupation depends on expected utility in that occupation, along with the expected utilities in the two adjacent occupations and the utility for nonparticipants. This generalizes the "mixed model" of Saez (2002) with

[3] The literature sometimes characterizes an EITC as a tax system featuring a negative marginal tax at the bottom, as in Saez (2002). Jacquet, Lehmann, and Van der Linden (2013) shows that this is a very local result: with a continuous income model, employment taxes feature a discontinuity at zero income and positive marginal tax rates at all income levels. Thus, we prefer to designate a tax system as corresponding to an EITC when the *employment tax* is negative at the bottom. Note that Hansen (2018) obtained both negative marginal and employment taxes at the bottom.

both intensive and extensive responses. There are several key differences in results that emerge. First, macro intensive and extensive responses appear instead of micro responses. This is because behavioral responses are captured by macro effects. Second, the social welfare weights need to be inflated to take into account that the macro effects of a tax reform on welfare differ from the micro ones. Finally, there is a new term since a change in the marginal tax rate may affect employment through a wage-moderating, employment-enhancing effect of tax progressivity. This force tends to increase optimal marginal tax rates as in models with search unemployment (see Hungerbühler et al. 2006; Lehmann, Parmentier, and Van der Linden 2011; Hummel 2018).

The second contribution of this paper is to numerically implement our optimal tax formula. Following Saez (2002), we restrict ourselves to our extension of the "mixed model." We implement the formula in part by calibrating some of the sufficient statistics and in part by estimating some of them. In particular, we focus on estimating the macro employment response to taxation and the micro and macro participation response to taxation. In order to identify the micro effects of taxation, we need a tax reform that holds wages and unemployment responses constant in a labor market. In other words, we require variation in tax liabilities across individuals *within* the same labor market. To identify macro responses to taxation, we require variation in tax liabilities *between* labor markets. Our empirical strategy focuses on single individuals in the United States and exploits policy variation in the tax-and-transfer system that operates over time, across states, and across households, which gives us three sources of policy variation. To estimate the micro participation response, we rely on time and household variation by exploiting reforms to the federal EITC that differentially affected single individuals depending on their number of children. The key assumption is that spillover effects uniformly affect individuals across different family structures (e.g., different number of children) operating in the same labor market. Thus, our difference-in-differences estimate will reflect only micro responses. For the macro employment and participation responses, we rely on policy variation across states and over time. Our identifying assumption is that spillover effects to state-specific tax policy operate within states, but not across them. Thus, our difference-in-differences estimate will capture both micro responses and spillover effects. To obtain both the micro and macro estimates, we isolate purely exogenous variation in tax liabilities coming from policy reforms, following the simulated instrumental variables (IV) approach in Currie and Gruber (1996) and Gruber and Saez (2002). Our IV estimates show that the micro participation elasticity, for the full sample of single individuals, is 0.57. Our estimates of the macro participation and employment elasticity are 0.48 and 0.42, respectively.

As an illustration, we use our empirical estimates to implement our sufficient statistics formula and calibrate the optimal income tax. We demonstrate three key results. First, the ratio of macro to micro participation responses has a large impact on the optimal tax policy: smaller macro responses move the optimal schedule more toward an NIT-like tax schedule with a relatively larger lump-sum payment to the nonemployed combined with higher employment tax rates and marginal tax rates. In particular, our empirical point estimates of the macro-micro participation ratio imply that the optimal tax schedule features a lump-sum payment that is around 17 percent higher than if this channel is ignored. Second, the employment-enhancing effect of tax progressivity also has a large impact on the optimal tax schedule—the larger this effect, the larger the lump-sum payment—while at the same time increasing the employment tax rates, as well as marginal tax rates at income levels where employment taxes are positive. Third, we use our, albeit somewhat noisy, empirical estimates of behavioral responses over the business cycle to show that during recessions the optimal income tax at the bottom shifts more toward an NIT-like structure with larger lump-sum transfers and higher marginal tax rates.

Our paper contributes to several strands of the literature. In the optimal tax literature, our paper relates to Stiglitz (1982); Saez (2004); Rothschild and Scheuer (2013); and Sachs, Tsyvinski, and Werquin (2016), who solve for the optimal income tax with endogenous wages but do not consider (involuntary) unemployment. Hungerbühler et al. (2006) and Golosov, Maziero, and Menzio (2013) derive the optimal income tax in models with search frictions and involuntary unemployment, but with exogenous wages. We show in the online Appendix that these models are special cases of our model.

Our framework also highlights the relevance of the micro-macro "wedge" as a corrective device in optimal tax models with spillovers. This insight was initially introduced in an unemployment insurance context by Landais, Michaillat, and Saez (2018a, b), who derive a generalization of the "Baily (1978)–Chetty (2006)" optimal unemployment insurance formula when there are spillovers. We show in the online Appendix how their model can be obtained as a particular case of an extension of our model that includes a tax on profits. While Landais, Michaillat, and Saez (2018a, b) focus on a dynamic model in a social insurance setting, we consider the problem of redistribution in a static setting. Thus, our paper should best be seen as complementary to their paper.

On the empirical side, we contribute to the literature that estimates micro and macro behavioral responses to taxation. Chetty, Friedman, Olsen, and Pistaferri (2011); Chetty, Guren, Manoli, and Weber (2011); Chetty (2012); and Jäntti, Pirttilä, and Selin (2015) have all tried to reconcile why taxation has a larger impact on employment at the macro (e.g., country) level compared with micro labor supply responses estimated from quasi-experimental research designs based on tax reforms. These studies use the terms "micro" and "macro" to correspond to the source of variation used to estimate elasticities. Macro estimates are identified from cross-country variation in tax rates, whereas micro estimates are identified from quasi-experimental studies. Our contribution to this literature is to use the same dataset and a consistent method to estimate both the micro and macro elasticities for the United States. We estimate the micro elasticity using micro data and control for labor market fixed effects. For the macro elasticity, we pool the data to the market level, control for year and state fixed effects, and rely on within-state differences over time in the tax-and-transfer system. Thus, differences between micro and macro estimates are less likely to be confounded by differences in sample and/or methodology.

The rest of the paper proceeds as follows. Section I develops our theoretical model. Section II contains details on institutional background and describes our data and empirical results. Section III considers the policy implications of our theoretical and empirical findings. The last section concludes.

I. The Theoretical Model

The size of the population is normalized to 1. There are $I+1$ "occupations", indexed by $i \in \{0,1,\ldots,I\}$. An "occupation" in this model is best interpreted as a technical construct that is distinct from the word's conventional meaning. It can be viewed as a set of jobs that pay the same wage. In the model, higher occupations require higher skills and thus higher wages. Occupation 0 corresponds to nonemployment. We denote the gross wage in occupation i (equivalently pretax earnings) by w_i, the net wage (or consumption) by c_i, and the tax liability by $T_i = w_i - c_i$.[4] The timing of the model is as follows:

- The government chooses the tax policy.
- Each individual m chooses an occupation $i \in \{0,\ldots,I\}$ to participate in. This is modeled through heterogeneous search costs in each occupation.
- For each occupation $i \in \{1,\ldots,I\}$, a fraction $p_i \in (0,1]$ of participants are employed, receive gross wage w_i, pay tax T_i, and consume the after-tax wage $c_i = w_i - T_i$. The remaining fraction $1-p_i$ of participants are unemployed.

Unlike in Saez (2002), we make a distinction among the *nonemployed* individuals between the *unemployed* who search for a job in a specific occupation but fail to find one and the *nonparticipants* who choose not to search for a job. For each occupation $i \in \{1,\ldots,I\}$, k_i denotes the number of participants; $p_i \in (0,1]$ denotes the fraction of them who find a job and work, hereafter the *conditional employment probability*; and $h_i = k_i p_i$ denotes the number of employed workers. The number of unemployed individuals in occupation i is $k_i - h_i = k_i(1-p_i)$, and the unemployment rate is $1-p_i$. The number of nonparticipants is k_0. The number of nonemployed is $h_0 = k_0 + \sum_{i=1}^{I} k_i(1-p_i)$.

We assume that all participants in occupation i face the same probability p_i of being employed. This "uniform rationing" assumption is made for tractability, just as the assumption that all employed in a given occupation are paid the same wage w_i. All the nonemployed, whether nonparticipants or unemployed, receive the same welfare benefit, denoted b. Therefore, the policy choice of the government is represented by the vector $\mathbf{t} = (T_1,\ldots,T_I,b)$.

The government faces the following budget constraint:

$$(1) \qquad \sum_{i=1}^{I} T_i h_i = b\, h_0 + E \quad \Leftrightarrow \quad \sum_{i=1}^{I} (T_i + b) h_i = b + E,$$

where $E \geq 0$ is an exogenous amount of public expenditures. One more employed worker in occupation i increases the government's revenues by the amount T_i of tax liability she pays plus the amount of welfare benefit b she no longer receives, the

[4] The assumption of a finite number of occupations is made for tractability. A continuous wage distribution can be approximated by increasing the number of occupations, I, to infinity.

sum of the two defining the *employment tax*.[5] The budget constraint states that the sum of employment tax liabilities $T_i + b$ collected on all employed workers in all occupations finances the public good plus a lump-sum rebate b over all individuals.

In the online Appendix, we consider several extensions of the model. First, we introduce a continuous job search intensity and obtain the same optimal tax formula. Second, we consider an extension of the model where the unemployed in occupation i receive a benefit b_i that may differ from the welfare benefit z given to non-participants. We show that the generalized formula depends on the same sufficient statistics. Finally, we consider an extension of the model with a partial tax on profits and show that the wage response to taxation is an additional sufficient statistic that one must account for in the optimal tax formula.

A. *Micro versus Macro Responses*

In the paper, we make a crucial distinction between macro and micro responses to taxes. On the one hand, we define *micro* responses to a tax change in the hypothetical case where tax changes do not affect gross wages $w_1, \ldots, w_I$ or conditional employment probabilities $p_1, \ldots, p_I$. This is, for instance, the case for tax reforms frequently considered in the microeconometric literature using difference-in-difference identification strategies. For these research designs, indirect or spillover effects of reforms typically affect wages and conditional employment probabilities in treatment and control groups in a uniform way. As a result, these research designs typically identify the micro or partial equilibrium effect of reforms.

On the other hand, *macro* responses to tax policy $\mathbf{t}$ are defined to encapsulate the general equilibrium responses of wages and conditional employment probabilities to taxes. To describe the latter, rather than specify microfoundations, we use reduced-form functions denoted $\mathcal{W}_i(\cdot)$, $\mathcal{C}_i(\cdot)$, and $\mathcal{P}_i(\cdot)$. In occupation i, the gross wage is given by $w_i = \mathcal{W}_i(\mathbf{t})$, the net wage is given by $c_i = \mathcal{C}_i(\mathbf{t}) \equiv \mathcal{W}_i(\mathbf{t}) - T_i$, and the conditional employment probability is given by $p_i = \mathcal{P}_i(\mathbf{t})$. At this general stage, we assume only that these functions are differentiable, that $\mathcal{P}(\cdot)$ takes values in $(0,1]$, and that $0 < \mathcal{W}_1(\mathbf{t}) < \cdots < \mathcal{W}_I(\mathbf{t})$ and $b < \mathcal{C}_1(\mathbf{t}) < \cdots < \mathcal{C}_I(\mathbf{t})$ for all tax policies $\mathbf{t}$. The two latter assumptions ensure that occupations indexed with a higher i correspond to occupations with higher before-tax and after-tax earnings.[6]

B. *Labor Supply Decisions*

Let $u(\cdot)$ be the cardinal representation of the utility individuals derive from consumption. This function is assumed to be increasing and weakly concave. Individual m faces, in addition, a utility cost $\chi_i(m)$ for searching for a job in occupation i, with the normalization $\chi_0(m) = 0$. Heterogeneity in $\chi_i(m)$ accounts for difference in the taste of work, but also for heterogeneity in skills. For instance, if

[5] The literature interprets this term as the *participation tax*, which is not strictly correct whenever unemployment is present.

[6] This assumption plays a similar role in our model to the single-crossing property in Mirrlees (1971).

individual m does not have the required skill to work in occupation i, it becomes extremely costly for her to apply to these jobs, in which case we consider that $\chi_i(m) = +\infty$.[7]

Individual m has a utility level equal to $u(c_i) - \chi_i(m)$ if she finds a job in occupation i, $u(b) - \chi_i(m)$ if she is unemployed in occupation i, and $u(b)$ if she chooses not to search for a job. Let

$$(2) \qquad \mathcal{U}_i(\mathbf{t}) \equiv \mathcal{P}_i(\mathbf{t}) u(\mathcal{C}_i(\mathbf{t})) + (1 - \mathcal{P}_i(\mathbf{t})) u(b)$$

denote the *gross* expected utility of searching for a job in occupation i, absent any participation cost, as a function of the tax policy $\mathbf{t}$, and let

$$U_i \equiv p_i\, u(c_i) + (1 - p_i) u(b)$$

denote its realization at a particular point of the tax system. Let $U_0 = u(b)$ be the utility expected out of the labor force. Individual m expects $U_i - \chi_i(m)$ by searching for a job in occupation i. She chooses to search in occupation i if and only if $U_i - \chi_i(m) > U_j - \chi_j(m)$ for all $j \in \{0, \ldots, I\} \setminus \{i\}$. Provided that the distribution of participation costs $(\chi_1, \ldots, \chi_I)$ is smooth enough, one can write the number k_i of participants in each occupation as a function denoted $\hat{\mathcal{K}}_i(\cdot)$ of gross expected utilities, so that

$$(3) \qquad k_i = \mathcal{K}_i(\mathbf{t}) \equiv \hat{\mathcal{K}}_i(\mathcal{U}_1(\mathbf{t}), \ldots, \mathcal{U}_I(\mathbf{t}), u(b)).$$

In other words, the tax policy influences participation decisions only through the determination of gross expected utilities. Therefore, to compute the micro and macro responses of participation to taxation, one needs first to compute the micro and macro responses of gross expected utilities to taxation. The micro response of expected utility in occupation i to taxation in occupation j is given by

$$(4) \qquad \left.\frac{\partial \mathcal{U}_i}{\partial T_j}\right|^{\text{Micro}} = -p_i\, u'(c_i)\, \mathbf{1}_{i=j},$$

while the macro one is given by

$$(5) \qquad \frac{\partial \mathcal{U}_i}{\partial T_j} = \left[\frac{\partial \mathcal{C}_i}{\partial T_j} + \frac{\partial \mathcal{P}_i}{\partial T_j} \frac{u(c_i) - u(b)}{p_i\, u'(c_i)}\right] p_i\, u'(c_i).$$

The micro and macro responses of expected utilities to taxation differ for two reasons. First, for micro responses, unlike for macro ones, gross wages are held constant. Therefore, if $i = j$, the tax change is passed through one for one to the worker and $\partial \mathcal{C}_i / \partial T_j = -1$. If $i \neq j$, the tax reform has no effect on before-tax and after-tax wages, so $\partial \mathcal{C}_i / \partial T_j = 0$. Conversely, for macro responses, tax adjustments may affect wages in a variety of ways, so, in general, $\partial \mathcal{C}_i / \partial T_j \neq -\mathbf{1}_{i=j}$. Second, at the

[7] We can extend the model to a utility cost that is specific to employed individuals in each occupation. The only consequence is notational.

micro level, the conditional employment probabilities are unaffected by a change in taxes. Conversely, at the macro level, responses of conditional employment probabilities have to be taken into account. They may be due to changes in labor supply or changes in vacancy creation by employers following gross wage responses. The matrix $(\mathbf{d}\mathcal{U}/\mathbf{dT})|^{\text{Micro}}$ of micro responses of expected utilities is diagonal, while the matrix $\mathbf{d}\mathcal{U}/\mathbf{dT}$ of macro responses may not be diagonal, in which case the tax liability in one occupation affects expected utility in another occupation.[8] We refer to the off-diagonal elements of the matrix of macro responses as "cross effects" throughout.

After applying the chain rule to (3) and using matrix notation, we find the macro and micro participation responses to taxation are given by $\mathbf{d}\mathcal{K}/\mathbf{dT} = \left(\mathbf{d}\mathcal{U}/\mathbf{dT}\right) \cdot (\mathbf{d}\hat{\mathcal{K}}/\mathbf{dU})$ and $\left(\mathbf{d}\mathcal{K}/\mathbf{dT}\right)|^{\text{Micro}} = \left(\mathbf{d}\mathcal{U}/\mathbf{dT}\right)|^{\text{Micro}} \cdot (\mathbf{d}\hat{\mathcal{K}}/\mathbf{dU})$. This leads us to the following lemma.

LEMMA 1: *If matrix* $\mathbf{d}\hat{\mathcal{K}}/\mathbf{dU}$ *is invertible, the matrix ratio of macro to micro participation responses is equal to the matrix ratio of macro to micro responses of gross expected utilities, i.e.,*

$$\text{(6)} \qquad \frac{\mathbf{d}\mathcal{U}}{\mathbf{dT}} \cdot \left(\frac{\mathbf{d}\mathcal{U}}{\mathbf{dT}}\bigg|^{\text{Micro}}\right)^{-1} = \frac{\mathbf{d}\mathcal{K}}{\mathbf{dT}} \cdot \left(\frac{\mathbf{d}\mathcal{K}}{\mathbf{dT}}\bigg|^{\text{Micro}}\right)^{-1}.$$

The effect of a government policy on individual welfare is summarized by how that policy affects the individual's gross expected utility. Since participation responses depend only on expected utilities, it follows that one may use the macro and micro participation responses to characterize how the effects of a policy on welfare differ at the macro level compared with the micro one.

Lastly, given our definitions of labor force participation and job-finding probabilities, employment is given by

$$\text{(7)} \qquad h_i = \mathcal{H}_i(\mathbf{t}) \equiv \mathcal{K}_i(\mathbf{t})\,\mathcal{P}_i(\mathbf{t}).$$

C. *Social Objective*

Choosing a social objective is a difficult issue as it relies on subjective value judgments. In this paper, we restrict the social objective to depend on the allocation only through the determination of expected utilities, so that the social objective is a function $\Omega\left(U_1, \ldots, U_I, u(b)\right)$ of gross expected utilities, which is nondecreasing in each of its $I + 1$ arguments. This is, for instance, the case for any weighted utilitarian social objective of the form

$$\Omega\left(U_1, \ldots, U_I, u(b)\right) = \int \gamma(m)\left(\max_i U_i - \chi_i(m)\right) d\mu(m),$$

[8] For any function f of $\mathbf{t} = (T_1, \ldots, T_I, b)$, we denote $\mathbf{df}/\mathbf{dT}$ the square matrix of rank I whose term in row j and column i is $\partial f_i/\partial T_j$ for $i,j \in \{1, \ldots, I\}$. Symmetrically, the corresponding matrix of micro responses is denoted $(\mathbf{df}/\mathbf{dT})|^{\text{Micro}}$. Finally, we denote $\mathbf{d}\hat{\mathcal{K}}/\mathbf{dU}$ the square matrix of rank I whose term in row j and column i is $\partial\hat{\mathcal{K}}_i/\partial U_j$ for $i,j \in \{1, \ldots, I\}$. In particular, these matrices do not include partial derivatives with respect to b. The operator "$\cdot$" denotes the matrix product. Superscript "-1" stands for the inversed matrix, while superscript "T"for the transposed matrix.

where the weights $\gamma(m)$ are type dependent and where $\mu(\cdot)$ is the distribution of types.

D. *The Optimal Policy*

The government chooses the tax policy $\mathbf{t} = (T_1, \ldots, T_I, b)'$ to maximize the social objective $\Omega(U_1, \ldots, U_I, u(b))$ subject to the budget constraint (1). Let $\lambda > 0$ denote the Lagrange multiplier associated with the latter constraint. The Lagrangian of the government can be written using reduced forms of the macro effects of taxes, independently of the microfoundations underlying these reduced forms:

$$(8) \qquad \Lambda(\mathbf{t}) \equiv \sum_{i=1}^{I} (T_i + b)\mathcal{H}_i(\mathbf{t}) - b - E + \frac{1}{\lambda}\Omega(\mathcal{U}_1(\mathbf{t}), \ldots, \mathcal{U}_I(\mathbf{t}), u(b)).$$

Following Saez (2002), we define the marginal social welfare weight of workers in occupation $i \in \{1, \ldots, I\}$ as "the value (in terms of public funds) of giving an additional dollar to an individual in occupation i." Because we defined micro responses as those occurring for unchanged wages w_i and employment probabilities p_i, the mechanical increase in social welfare after a rise in consumption in occupation i is equivalent to the micro effect on social objective of a cut in tax liability in occupation i. We thus get:[9]

$$(9) \qquad g_i \equiv -\frac{1}{\lambda h_i} \frac{\partial \mathcal{U}_i}{\partial T_i}\bigg|^{\text{Micro}} \frac{\partial \Omega}{\partial U_i} \quad \Leftrightarrow \quad \frac{1}{\lambda}\frac{\partial \Omega}{\partial U_i} = -\left(\frac{\partial \mathcal{U}_i}{\partial T_i}\bigg|^{\text{Micro}}\right)^{-1} g_i h_i.$$

The social weight g_i represents the social value in monetary terms of transferring an additional dollar to an individual working in occupation i, ignoring the responses of wages and of the conditional employment probabilities. It is nonnegative according to (4). Absent these responses, the government is indifferent between giving one more dollar to an individual employed in occupation i and allocating g_i more dollars of public funds.

Using (9), the first-order condition with respect to the tax liability T_j in occupation j is

$$(10) \qquad 0 = \underbrace{h_j}_{\text{Mechanical effect}} + \underbrace{\sum_{i=1}^{I} (T_i + b)\frac{\partial \mathcal{H}_i}{\partial T_j}}_{\text{Behavioral effects}} \underbrace{- \sum_{i=1}^{I} \frac{\partial \mathcal{U}_i}{\partial T_j}\left(\frac{\partial \mathcal{U}_i}{\partial T_i}\bigg|^{\text{Micro}}\right)^{-1} g_i h_i}_{\text{Social Welfare effects}}.$$

A unit increase in the tax liability T_j triggers the following effects:

- **Mechanical Effect:** Absent any behavioral response, a unit increase in T_j increases the government's resources by the mass h_j of employed individuals in occupation j.

[9] See Saez and Stantcheva (2016) when the social objective is not welfarist.

- **Behavioral Effects:** A unit increase in T_j induces a change $\partial\mathcal{H}_i/\partial T_j$ in the level of employment in occupation i. This change incorporates general equilibrium (macro) responses. For each additional worker in occupation i, the government increases its resources by the employment tax $T_i + b$, which is equal to the additional tax T_i received plus the benefit b that is no longer paid.
- **Social Welfare Effects:** A unit increase in T_j affects the expected utility in occupation i by $\partial\mathcal{U}_i/\partial T_j$. Multiplying by the rate $\left(\partial\Omega/\partial U_i\right)/\lambda$ at which each unit change in expected utility affects the social objective in monetary terms, we get that the social welfare effect of tax T_j in occupation i is: $\frac{\partial\mathcal{U}_i}{\partial T_j}\frac{1}{\lambda}\frac{\partial\Omega}{\partial U_i} = -\frac{\partial\mathcal{U}_i}{\partial T_j}\left(\frac{\partial\mathcal{U}_i}{\partial T_i}|^{\text{Micro}}\right)^{-1} g_i h_i$. Note that because the social welfare function depends on expected utility U_i, the labor supply responses modify only the decisions of individuals who are initially indifferent between two occupations, and thus have only second-order effects on the social welfare objective, by the envelope theorem (Saez 2001, 2002). Conversely, wage and unemployment responses are general equilibrium (macro) responses induced by the market instead of being directly triggered by individual choices. Thus, one must consider the macro responses of expected utility $\partial\mathcal{U}_i/\partial T_j$ instead of the micro ones $(\partial\mathcal{U}_i/\partial T_i)|^{\text{Micro}}$. As the social weights are defined in terms of the micro effects of a tax change on the social objective, the usual social welfare terms $g_i h_i$ have to be inflated by the ratio between the macro and the micro responses of expected utility to taxation.

We now restate our optimal tax formula in terms of sufficient statistics. For this purpose, it is convenient to use matrix notation. Let $\mathbf{h} = \left(h_1, \ldots, h_I\right)'$ denote the vector of employment levels, let $\mathbf{gh} = \left(g_1 h_1, \ldots, g_I h_I\right)'$ denote the vector of welfare weights times employment levels, and let $\left(\mathbf{T} + \mathbf{b}\right) = \left(T_1 + b, \ldots, T_I + b\right)'$ denote the vector of employment taxes. We get the following result.

PROPOSITION 1: *If* $\mathbf{d}\hat{\mathcal{K}}/\mathbf{dU}$ *is invertible*, *the optimal tax system for occupations* $i = \{1, \ldots, I\}$ *solves*

$$(11) \qquad \mathbf{0} = \mathbf{h} + \frac{\mathbf{d}\mathcal{H}}{\mathbf{dT}} \cdot (\mathbf{T} + \mathbf{b}) - \frac{\mathbf{d}\mathcal{K}}{\mathbf{dT}} \cdot \left(\frac{\mathbf{d}\mathcal{K}}{\mathbf{dT}}\bigg|^{\text{Micro}}\right)^{-1} \cdot (\mathbf{gh}).$$

PROOF:
Equation (10) can be rewritten in matrix notation:

$$(12) \qquad \mathbf{0} = \mathbf{h} + \frac{\mathbf{d}\mathcal{H}}{\mathbf{dT}} \cdot (\mathbf{T} + \mathbf{b}) - \frac{\mathbf{d}\mathcal{U}}{\mathbf{dT}} \cdot \left(\frac{\mathbf{d}\mathcal{U}}{\mathbf{dT}}\bigg|^{\text{Micro}}\right)^{-1} \cdot (\mathbf{gh}).$$

Using equation (6) in Lemma 1 leads to (11). ∎

Due to the presence of wage and unemployment responses, our optimal tax formula differs from equation (11) in Saez (2002) in two important ways. First, the behavioral effects depend on the macro responses of employment, not the micro labor supply responses. Second, as the welfare weights are computed from the micro effects of a tax reform on the social objective and the macro responses are relevant to characterize the optimal tax, one needs a correcting procedure, which consists in multiplying the (vector of) welfare weights times employment levels by the (matrix) ratio of macro to micro responses of expected utilities, as in equation (12). From (5), estimating this ratio requires estimating the macro responses of wages to taxation, which are especially difficult to identify in practice. However, as participation decisions depend on taxation only through expected utilities, according to Lemma 1, the matrix ratio of macro over micro responses of expected utility to taxation coincides with the matrix ratio of macro over micro participation responses, which can be identified more easily, as will be illustrated in Section II.[10]

E. *The No-Cross-Effect Case*

We now specialize our model in order to compare our results to the pure extensive model in Saez (2002). For this purpose, we consider the no-cross-effect case where $\partial \mathcal{W}_i/\partial T_j = \partial \mathcal{C}_i/\partial T_j = \partial \mathcal{P}_i/\partial T_j = \partial \hat{\mathcal{K}}_i/\partial U_j = 0$ for $i \neq j$ and $i \neq 0$. This means that labor demand responds to tax liabilities only in the occupation, but not in other occupations. It also implies that labor supply responses are concentrated along the extensive margin. In other words, individuals can move from nonemployment to work (or vice versa) in a single occupation, but they cannot move between occupations in response to a tax change. The no-cross-effect assumption implies from (5) that $\partial \mathcal{U}_i/\partial T_j = 0$ and thereby $\partial \mathcal{K}_i/\partial T_j = \partial \mathcal{H}_i/\partial T_j = 0$ for $i \neq j$; i.e., that the wage, the conditional employment probability, the employment level, and the participation level in one occupation depend only on the welfare benefit b and on the tax liability in the same occupation, and not on tax liabilities in the other occupations. Therefore, the matrices of behavioral responses in (11) are all diagonal under the no-cross-effect assumption.

Let the micro participation elasticity be defined as $\pi_j^m \equiv -\frac{c_j - b}{k_j}\frac{\partial \mathcal{K}_j}{\partial T_j}\big|^{\text{Micro}}$, the macro participation elasticity as $\pi_j \equiv -\frac{c_j - b}{k_j}\frac{\partial \mathcal{K}_j}{\partial T_j}$, and the macro employment elasticity as $\eta_j \equiv -\frac{c_j - b}{h_j}\frac{\partial \mathcal{H}_j}{\partial T_j}$. From (7), the macro *employment* response η_j verifies $\eta_j = \frac{c_j - b}{p_j}\frac{\partial \mathcal{P}_j}{\partial T_j} + \pi_j$. It includes conditional employment responses $\frac{c_j - b}{p_j}\frac{\partial \mathcal{P}_j}{\partial T_j}$ in addition to the macro *participation* responses π_j. Equation (11) then simplifies to the following.

PROPOSITION 2: *The optimal tax in occupation j in the no-cross-effect case is*

$$\frac{T_j + b}{c_j - b} = \frac{1 - \frac{\pi_j}{\pi_j^m} g_j}{\eta_j}. \tag{13}$$

The no-cross-effect environment is the simplest one in which to understand how the introduction of unemployment and wage responses modifies the optimal tax formula.

[10] We derive the optimal condition for the benefit level in Appendix A. We also show there that when income effects are assumed away, welfare weights sum to 1, i.e., $\sum_{i=0}^{I} g_i h_i = 1$.

In the pure extensive case without unemployment, Diamond (1980), Saez (2002), and Choné and Laroque (2005, 2011) showed that the optimal tax formula takes the form of an inverse elasticity rule $(T_j + b)/(c_j - b) = (1 - g_j)/\eta_j$. There are two key differences between the latter equation and equation (13). First, the denominator in (13) corresponds to the macro employment elasticity. Second, equation (13) inflates the social marginal welfare weight by the ratio of the macro to micro participation elasticity. As explained in Lemma 1, this is to account for the macro effects of taxation on the social objective, since the welfare weights are defined in terms of the micro expected utility responses. To understand why, consider a decrease in tax liability T_j in the no-cross-effect case. This triggers a positive direct impact on social welfare $g_j h_j$, which is the only one at the micro level. Moreover, this decrease in tax liability typically induces a decrease in the gross wage when $\partial \mathcal{W}_j / \partial T_j > 0$, so the wage response attenuates the direct impact on social welfare. Finally, the decrease in tax liability also typically triggers a rise in job creation, whenever $\partial \mathcal{P}_j / \partial T_j < 0$, so the response of the conditional employment probability reinforces the direct impact on social welfare. The macro response of participation to taxation is therefore larger (smaller) than the micro one if the impact of the conditional employment response dominates (is dominated by) the impact of the wage response. Proposition 2 implies the following.

COROLLARY 1: *In the no-cross-effect case, the optimal employment tax for the working poor is negative whenever* $g_1 > \pi_1^m / \pi_1$.

According to (13), a negative employment tax (EITC) becomes optimal whenever the social welfare weight is higher than the ratio of the micro over the macro participation elasticity, instead of higher than one in the case without unemployment and wage responses.

In principle, the macro participation elasticity can be either larger or lower than the micro participation elasticity. In the online Appendix, we consider a search-and-matching model where for each occupation, unemployment arises because of matching frictions along the lines of Mortensen and Pissarides (1999), wages are set by proportional bargaining, the production function is linear, and workers are risk neutral. This model is a structural version of our no-cross-effect environment.[11] In such a model, a rise in tax liability is shared between the worker and the firm, so the after-tax wage decreases while the pretax wage increases. The latter reduction in turn induces firms to post fewer vacancies, which depresses labor demand and increases unemployment. The rise in pretax income tends to attenuate the effect of the tax increase on workers' consumption and leads to lower responses of expected utility at the macro level compared with the micro one. Conversely, the decrease in the employment probability tends to lead to lower responses of expected utility at the macro level compared with the micro one. We show that the micro and macro participation responses are equal

[11] Under proportional bargaining (e.g., Jacquet, Lehmann, and Van der Linden 2014), the firm and the worker get a share of the surplus that does not depend on the marginal tax rate, which is no longer the case under monopoly union (Hersoug 1984), Nash bargaining (Pissarides 1985, Lockwood and Manning 1993, Hungerbühler et al. 2006), or competitive search models (Lehmann, Parmentier, and Van der Linden 2011), where a compensated increase in the marginal tax rate induces workers to concede wage moderation for higher employment.

under the Hosios (1990) condition where the workers' bargaining power is equal to the elasticity of the matching function with respect to unemployment. Moreover, if the worker's bargaining power is instead lower (larger) than the elasticity of the matching function, the macro response is lower (larger) than the micro one.

Estimating the ratio of the macro to micro participation elasticity is therefore sufficient to conclude whether unemployment and wage responses make the EITC more or less optimal in the case where there are no cross effects.

F. *The Case with Intensive and Extensive Responses*

In this section, we extend the optimal tax formula of Saez (2002) with both intensive and extensive margins for the presence of wage and unemployment responses to taxation. For this purpose, we assume that wages $\mathcal{W}_i(\cdot)$ and employment probabilities $\mathcal{P}_i(\cdot)$ in a given occupation depend only on the tax liability T_i in that occupation, on tax liabilities in the two adjacent occupations T_{i+1} and T_{i-1}, and on the welfare benefit b. Moreover, participation in given occupation $\hat{\mathcal{K}}_i(\cdot)$ depends only on expected utility U_i in that occupation, on expected utilities in the two adjacent occupations U_{i+1} and U_{i-1}, and on utility out of the labor force $U_0 = u(b)$. Combining with equations (2), (3), and (7), employment $\mathcal{H}_i(\cdot)$ in a given occupation therefore depends only on the tax liability T_i in that occupation, on tax liabilities in the two adjacent occupations T_{i+1} and T_{i-1}, and on the welfare benefit b. We can therefore reexpress employment in a given occupation as a function

$$\mathcal{H}_i(\mathbf{t}) \equiv \tilde{\mathcal{H}}_i(T_i, T_{i+1} - T_i, T_i - T_{i-1}, b) \tag{14a}$$

of the tax liability T_i in that occupation, the two marginal tax rates $T_{i+1} - T_i$ and $T_i - T_{i-1}$, and the welfare benefit b. Let

$$\zeta_i \equiv -\frac{c_i - c_{i-1}}{h_i} \frac{\partial \tilde{\mathcal{H}}_i}{\partial(T_i - T_{i-1})} \tag{14b}$$

define the macro behavioral elasticity that captures intensive responses and—following Saez (2002)—is called the mobility elasticity. This can be related to the standard *intensive* elasticity of earnings with respect to marginal tax rates. In the competitive model of Saez (2002), this intensive margin elasticity is due only to individuals deciding to work in occupation $i - 1$ instead of working in occupation i when the marginal tax rate $T_i - T_{i-1}$ increases, which implies $\frac{\partial \tilde{\mathcal{H}}_{i-1}}{\partial(T_i - T_{i-1})} + \frac{\partial \tilde{\mathcal{H}}_i}{\partial(T_i - T_{i-1})} = 0$. Conversely, in models with wage and unemployment responses to taxation, a change in the marginal tax rate may trigger additional effects. For instance, a compensated increase in the marginal tax rate induces a wage moderation in many models of the labor market: it induces a substitution of employment for wage in monopoly union models (Hersoug 1984) and in competitive search equilibrium models (Lehmann, Parmentier, and Van der Linden 2011), and it induces a substitution of profits for wage in wage bargaining models (Lockwood and Manning 1993), in search and matching models with Nash bargaining (Pissarides 1985, 1998), and in efficiency wage models (Pisauro 1991). Such wage-moderating effects may in turn induce firms to hire more workers, thereby generating an "employment-enhancing effect of tax progressivity". We therefore introduce the following sufficient statistic to capture this effect:

$$\mu_i \equiv \frac{c_i - c_{i-1}}{h_i}\left(\frac{\partial \tilde{\mathcal{H}}_{i-1}}{\partial(T_i - T_{i-1})} + \frac{\partial \tilde{\mathcal{H}}_i}{\partial(T_i - T_{i-1})}\right). \tag{14c}$$

The statistic captures how much total employment in occupation i and $i-1$ changes in response to a change in the marginal tax rate. Finally, changes in tax liabilities that are not associated with a change in marginal tax rates generate employment effects that are captured by

$$\eta_i \equiv -\frac{c_i - b}{h_i}\frac{\partial \tilde{\mathcal{H}}_i}{\partial T_i}. \tag{14d}$$

Note that η_i captures both extensive responses and income responses. We show the following proposition in Appendix B.

PROPOSITION 3: *When employment responses verify* (14a), *the optimal tax has to verify*

$$\frac{T_i - T_{i-1}}{c_i - c_{i-1}} = \frac{\mu_i}{\zeta_i}\frac{T_{i-1} + b}{c_i - c_{i-1}} + \frac{1}{\zeta_i h_i}\sum_{j=i}^{I}\left(1 - \hat{g}_j - \frac{T_j + b}{c_j - b}\eta_j\right)h_j, \tag{15}$$

where the inflated welfare weights $\hat{g}_1, \ldots, \hat{g}_I$ *are defined by the matrix identity:*

$$(\hat{g}_1 h_1, \ldots, \hat{g}_I h_I)^T = \frac{\mathbf{d}\mathcal{K}}{\mathbf{dT}} \cdot \left(\frac{\mathbf{d}\mathcal{K}}{\mathbf{dT}}\bigg|^{\text{Micro}}\right)^{-1} \cdot (\mathbf{gh}). \tag{16}$$

To understand the economics behind the optimal tax formula (15), let us consider a small increase[12] dT in tax liabilities in occupations $j = i, i+1, \ldots, I$. We thus have: $dT = dT_i = dT_{i+1} = \cdots = dT_I$. This tax change raises $[h_i + h_{i+1} + \cdots + h_I]dT$ additional taxes through the mechanical effect, which are valued $[(1 - \hat{g}_i)h_i + (1 - \hat{g}_{i+1})h_{i+1} + \cdots + (1 - \hat{g}_I)h_I]dT$ by the government. The change in tax liabilities in occupations $j = i, i+1, \ldots, I$ also induces extensive and income responses that change the level of employment in occupations $j = i, i+1, \ldots, I$ by $dh_j = (\eta_j h_j/(c_j - b))dT$. These responses in turn modify the government's revenue by $(T_j + b)dh_j = \frac{T_j + b}{c_j - b}\eta_j h_j dT$. Finally, the marginal tax rate between occupation $i-1$ and i increases. This induces behavioral responses that can be decomposed in two terms. First, as in Saez (2002), a flow $(\zeta_i/(c_i - c_{i-1}))h_i$ of workers switch from occupation i to occupation $i-1$, which reduces government revenue by $\frac{T_i - T_{i-1}}{c_i - c_{i-1}}\zeta_i h_i$. Moreover, some additional jobs in occupation $i-1$ may be created through the employment-enhancing effect, which implies a change in tax revenue equal to $\frac{T_{i-1} + b}{c_i - c_{i-1}}\mu_i h_i$.

[12] The case $dT < 0$, where tax liabilities are decreased, is obviously symmetric.

There are three differences between our optimal tax formula (15) and the optimal tax formula of Saez (2002) with both intensive and extensive responses. First, instead of the micro intensive and extensive elasticities, it is the macro mobility elasticity ζ_i and the macro tax liability elasticity η_i that show up in (15). This is because behavioral responses are not only generated by micro responses. Moreover, we do not rule out income effects. Second, the welfare weights need to be adjusted to take into account that the macro effects of a tax reform on welfare differ from the micro ones. This is the reason why it is the inflated welfare weights $\hat{g}_i$ that show up and not the usual welfare weights g_i. Last, a change in the marginal tax rate may not only generate a flow of employment between two consecutive occupations, but may also increase the overall employment level, for instance through a wage-moderating, employment-enhancing effect. In that case, one gets that $\mu_i > 0$. Moreover, if the optimal employment tax $T_i + b$ is positive, this employment-enhancing effect of tax progressivity is an additional force that tends to increase optimal marginal tax rates, as in optimal tax models with search unemployment from Hungerbühler et al. (2006); Lehmann, Parmentier, and Van der Linden (2011); and Hummel (2019).

II. Estimating Sufficient Statistics

Our optimal tax formula (15) shows that the macro employment response to taxes and the micro and macro participation responses are among the set of sufficient statistics. While a large number of studies have estimated micro responses, few have estimated macro responses, and many do not distinguish between participation and employment responses. Our objective in this section is to estimate micro and macro extensive-margin responses for both employment and participation using a consistent methodology for the US population.

We take a local labor market approach and define a geographic labor market by location (state), education, and time (year-month). To identify macro responses, it is necessary to have exogenous variation in tax liabilities at the level of the local labor market. For micro estimates, we need exogenous variation between individuals within a given labor market.

A. *Data*

Current Population Survey.—We follow the large empirical literature on the effects of the EITC and welfare reform in the United States and focus on low-income, single individuals throughout the past three decades. As a consequence of the gradual expansion of the EITC and the 1990s welfare reform, this group experienced substantial changes in participation and marginal tax rates differentially by number of children, within and across states.

Our analysis is based on data from the monthly outgoing rotation group (ORG) and the March annual data from the Current Population Survey (CPS). The March annual data span the time period 1984–2011, while the ORG data (from IPUMS) span 1994–2010. As our analysis sample, we select all single individuals age 18 to 55 who are not in the military or enrolled full time in school or college. Since there is insufficient tax variation for higher income individuals over our sample period, and since lower income individuals are more likely to be on the margin of the labor force, we further restrict the sample to individuals with education less than a bachelor's degree. Our theory distinguishes between individuals who choose to participate in the labor force (and are employed or unemployed) and individuals who are actually employed. We measure these labor market states using the standard International Labor Office criteria. A person is classified as being in the labor force if she was either employed or unemployed (i.e., was actively looking for a job during the reference week and was available for work) and employed if she was working during the reference week (or was temporarily absent from a job).[13]

Panel A of Table 1 shows descriptive statistics for the demographic characteristics of single individuals in the March CPS for the full sample (column 1) and broken down by educational attainment groups (columns 2–4), pooling all years from 1984 to 2011.[14] The age range is similar across the three education groups—less than high school, high school, and some college—but there are large differences in the distribution of number of children, with lower educated single individuals being more likely to be parents. This is likely due to our sample restriction to singles since higher educated parents are more likely to be married. Additionally, low-educated individuals are more likely to be black or Hispanic than high-educated ones. Panel B displays labor market variables by educational attainment. Lower educated individuals are much less likely to be in the labor force than higher educated ones and also experience higher unemployment rates.

Tax-and-Transfer Calculator.—In order to estimate the employment and participation effects of taxes and transfers it is necessary to compute the budget sets that individuals face. For this purpose, we developed a calculator that computes taxes and transfers at (nominal) income levels for single individuals, depending on the number of children, state, and year. We assume that an individual is filing as the head of the household and is claiming his or her children as dependents. To compute taxes (covering federal and state income taxes, including tax credits, as well as FICA liability), we rely on the National Bureau of Economic Research TAXSIM software. We assign taxes on the basis of state of residence, as reported in the CPS, as well as number of children, year, and income.[15] To compute transfers, in particular Aid to Families with Dependent Children (AFDC), Temporary Assistance for Needy Families (TANF), and Supplemental Nutrition Assistance Program (SNAP), we construct a benefit calculator based on rules published in the Welfare Rules Database, managed by the Urban Institute. This allows us to compute the benefits an individual is eligible for, as a function of number of children, state of residence, year, and income. The shift from AFDC to TANF introduced a number of additional

[13] For complete details on sample construction and variable definitions, please see the online Appendix.

[14] We do not include the CPS ORG in this table since it spans different years, but when we compare sample means for the March CPS and ORG for the same period, they are extremely close.

[15] For an individual who resides and works in different states, the following rules apply. Generally an individual is required to pay income tax to her state of residence first. Then she must file as a nonresident in the state where she works, but she gets to take the amount of tax paid to the state of residence as a tax credit and pays only the difference. If the amount of tax paid to the state of residence is greater than the tax bill for the work state, the individual doesn't pay anything to the work state, but she still has to file. We don't take this into account in computing tax liabilities.

TABLE 1—VARIABLE MEANS FOR SINGLE INDIVIDUALS

	Estimation sample (1)	High school dropout (2)	High school graduate (3)	Some college (4)
Panel A. Demographics				
Age	32.9	32.3	32.7	33.5
Percent no children	79.4	77.1	80.2	79.6
Percent 1 child	10.9	10.3	10.8	11.5
Percent 2 children	6.2	6.8	6.0	6.2
Percent 3+ children	3.4	5.8	3.0	2.7
Mean years of education	11.9	9.2	12	13.3
Percent black	17.5	20.6	17.7	15.5
Percent Hispanic	14.2	29.2	11.5	9.5
Panel B. Labor force status				
Labor force participation rate (k_i)	80.8	65.2	82.7	87.0
Employment rate (h_i)	72.9	54.1	74.5	81.1
Unemployment rate $(1 - p_i)$	10.3	17.2	10.0	6.8
Panel C. Income, taxes, and transfers (real 2010 USD)				
Imputed pretax wage earnings	19,268	11,878	19,197	23,456
Real total post-tax-and-transfer income with take up: OLS	15,618	11,067	15,513	18,278
Net taxes: no children	4,674	2,349	4,638	5,968
Net taxes: 2 children	−76	−1,633	−400	1,292
AFDC/TANF and food stamps: no children	499	1,086	440	261
AFDC/TANF and food stamps: 2 children	3,476	6,805	3,245	1,726
Net tax and transfers (T_i): no children	4,175	1,264	4,197	5,707
Net tax and transfers (T_i): 2 children	−3,552	−8,438	−3,645	−435
Net tax and transfers (b): zero income, no children	−2,071	−2,055	−2,073	−2,078
Net tax and transfers (b): zero income, 2 children	−11,646	−11,693	−11,640	−11,627
AFDC/TANF recipiency rate for mothers: pre-1996	25	43	21	15
AFDC/TANF recipiency rate for mothers: post-1996	9	17	8	5
Food stamp recipiency rate: pre-1996	12	25	11	6
Food stamp recipiency rate: post-1996	14	25	14	10
Number of observations	1,817,083	350,817	832,919	633,347

Notes: The sample is restricted to single men and women aged 18–55. All dollar figures are in real 2010 USDt. Data used in each column are restricted to individuals with the education level in the column header. Imputed earnings result from a linear regression of demographics on wages conditional on employment. Net taxes is federal, state, and FICA (sum of employer and employee) tax liabilities net of tax credits, including EITC. AFDC/TANF and food stamps assume 100 percent recipiency among those eligible based on income. Net taxes and transfers is the net of federal, state, and FICA (sum of employer and employee) tax liabilities and credits, AFDC or TANF payments, and food stamp benefits.

work and eligibility requirements for welfare recipients. For example, federal rules require a minimum number of TANF recipients to be employed, and the lifetime duration of receiving TANF benefits is limited to a total of five years.[16] Rather than incorporate all of these policies explicitly into our empirical framework, we multiply benefits by gender-specific recipiency rates constructed from the Survey of

[16] In general, a state must have 50 percent of its single-parent households and 90 percent of its dual-parent households engaged in work-related activities (these include not only work but searching for work or taking training courses) for a minimum number of hours per week (30 hours per week, or 20 hours per week if there is a young child). The 50 percent and 90 percent figures are calculated from a pool of "work-eligible individuals" that does not include single parents of children under the age of 1. States can obtain credits against the 50 and 90 percent rates for overall caseload reduction.

Income and Program Participation. The new eligibility requirements are reflected in lower observed recipiency rates in our sample post welfare reform.

We use our tax-and-transfer calculator to compute the incentive to work. Since we focus solely on the extensive margin in our analysis, we capture work incentives using just two measures: the transfer an individual receives when she has zero income and the tax-and-transfer level at the earnings level an individual obtains when working. A key difficulty is that earnings, and hence tax liabilities, are unobserved for nonemployed individuals. Moreover, earnings for employed workers may be endogenous to the tax system. We proceed using two approaches. First, we impute an individual's tax liability following the approach taken in Eissa and Hoynes (2004) and Gelber and Mitchell (2012). We run separate regressions for each education group and year of log annual earnings for individuals on state fixed effects and control variables.[17] The control variables include a quadratic function of age, dummy variables for black and Hispanic, and a categorical variable describing geographic location (i.e., urban versus rural). For each individual in our sample (both the nonemployed and employed), we construct predicted earnings using the regression coefficients estimated from our model. This is for the purpose of obtaining a consistent specification.[18] We then use predicted earnings to impute an individual's tax liability using TAXSIM and the benefit calculator described above. In the online Appendix, we present ordinary least squares (OLS) regressions of participation and employment using this imputed tax liability.

One problem with this approach is that the demographic distribution itself, and therefore the imputed tax liabilities, might be endogenous to tax policy. For instance, more generous transfers to singles with kids, but not to individuals without children, may boost fertility and impact earnings. To address this concern, we also rely on a simulated instrument approach based on Currie and Gruber (1996).[19] This approach isolates policy variation in tax liabilities since it uses a fixed income and demographic distribution during the sample period.

Panel C of Table 1 shows the mean imputed real earnings for each education group averaged over the years and the corresponding tax-and-transfer levels depending on the number of children in the household. All numbers are reported in real 2010 US dollars. For high school dropouts, taxes (transfers) are strongly decreasing (increasing) in the number of children. This partly reflects the EITC, which reduces tax liabilities according to the number of children in the household. The welfare benefit for households with no children is driven entirely by SNAP since these households are ineligible for AFDC/TANF. For bachelor's degree holders (not shown), the range is very small and close to 0 since most are ineligible for these mean-tested benefits. Importantly, the reported welfare benefits do not incorporate

[17] For this exercise, we use earnings from the March CPS. To deal with misreporting, we also drop observations where the implied hourly wage is less than \$1 or greater than \$100 dollars.

[18] As an alternative, we tried performing a Heckman selection correction to control for self-selection using the number of children and the presence of young children in the selection equation. However, we found that the pattern of results was not very well behaved. In particular, predicted earnings for high school dropouts seemed too high, and earnings for higher education levels seemed unrealistically low relative to the raw differences in earnings across education groups. This is likely due to the lack of a convincing instrument for working.

[19] Gruber and Saez (2002) use this approach to estimate taxable income elasticities; however, we are not aware of any papers that use this approach to estimate extensive margin labor supply responses.

recipiency rates, which are much less than 100 percent during our sample period. The last four rows report recipiency rates, as estimated in the Survey of Income and Program Participation. Each individual in the CPS is assigned a recipiency rate that we calculate from the Survey of Income and Program Participation on the basis of gender, education, income, and year for individuals in the eligible income range. The table reports the average of the assigned recipiency rates separately for AFDC/TANF and food stamps, and also pre- and post-1996. We see that for high school dropouts, recipiency rates are roughly 50 percent for AFDC/TANF but fall to 20 percent post-1996. For food stamps, recipiency rates are much more comparable pre- and post-1996 and are equal to roughly 40 percent.[20] These recipiency rates decrease with education, which reflects diminishing eligibility as earnings increase.

B. *Empirical Method*

Let i denote households, e denote education level, n denote the number of children in the household, s denote state of residence, and t denote time. Our econometric specification to estimate the micro participation response is given by

$$k_{i,e,n,s,t} = T_{e,n,s,t}\beta + \delta_{e,s,t} + \delta_{e,n} + X_{i,e,n,s,t}\lambda + \varepsilon_{i,e,n,s,t}. \tag{17}$$

The employment tax liability is defined as $T_{e,n,s,t}$ and is the tax liability at an income level plus the transfers at 0 income. Implicit in this definition is the assumption that there are no income effects.[21] The term $\delta_{e,s,t}$ denotes labor market fixed effects interacted with education groups (one fixed effect for each state-by-year-by-month-by-education cell), $\delta_{e,n}$ are number of children $\times$ education group fixed effects, and $X_{i,e,n,s,t}$ are controls (demographic variables such as age, age squared, race, and ethnicity all interacted with education groups).[22] The coefficient β captures the micro participation effect.

Next, to estimate macro participation responses, we aggregate the data to state-year-education averages to get

$$k_{e,s,t} = T_{e,s,t}\gamma + \delta_{e,s} + \delta_{e,t} + X_{e,s,t}\lambda + \varepsilon_{e,s,t}. \tag{18}$$

Here, $T_{e,s,t}$ is the macro employment tax; $\delta_{e,s}$ and $\delta_{e,t}$ are education $\times$ state and education $\times$ year fixed effects, respectively; and $X_{e,s,t}$ is a vector of controls, including region-specific linear time trends and demographic characteristics (cell averages of the micro controls) interacted with education. The macro effect, γ, is defined as the change in individual participation probabilities if the tax liabilities for all indi-

[20] For AFDC/TANF, we calculate recipiency rates on the basis of the sample of single parents since singles with no children are not eligible for these programs.

[21] We tested whether the condition $\partial K_i/\partial T_i = \partial K_i/\partial b$ holds and found that the difference was very small and statistically insignificant. We therefore report only results under the no income effect assumption.

[22] Moffit (1998) argues that the literature features very heterogeneous marriage and fertility responses to taxes and transfers across studies, with a large number of studies finding no effect. As a result, he concludes that much more research remains to be done.

viduals in a labor market increase by one dollar. Finally, to estimate macro employment responses, we simply replace participation k with employment h.

In our model, the behavioral responses are measured in terms of the number of individuals employed in and participating in the labor market. However, for an empirical specification that uses variation across individuals and labor markets, it makes little sense to use levels and assume constant effects (across labor markets). Instead, we will estimate the effect of taxes on employment and participation *rates*. Estimating the marginal effects of taxes on employment and participation rates furthermore has the important advantage that the estimates are easier to interpret and compare with the prior literature.

Identification.—To identify the parameter β, we require that the micro tax liability $T_{e,n,s,t}$ is exogenous, conditional on labor market and education $\times$ number of children fixed effects and observables. Similarly, our identifying assumption for γ is that the macro tax liability $T_{e,s,t}$ is exogenous, conditional on education $\times$ state and education $\times$ year fixed effects and observables. Thus, two independent sources of exogenous variation in tax liabilities are needed. For the micro response β, we require variation in tax liabilities across individuals *within* the same labor market. For the macro response γ, we require variation in average tax liabilities *between* labor markets.

As described above, our strategy is to generate such variation using a simulated instrument approach. The policy variation in the micro tax liability is illustrated in panel A of Figure 1. This figure plots the average value of the micro simulated tax liability by year and number of children relative to the value in 1984 for high school dropouts. One can see that there is substantial variation in taxes over time and that this variation is very different across the number of children. Much of this is driven by the EITC. In particular, the 1986 Tax Reform Act reform can be clearly seen in 1986–1987 but is quite small relative to the expansions in the 1990s, which also introduced differential EITC levels for parents with one or two children. Finally, in 2009, the EITC was expanded for parents with three children, as can be seen in the figure, and income taxes were cut for all family types. The identification strategy is similar to the one used in Eissa and Liebman (1996), Meyer and Rosenbaum (2001), and Gelber and Mitchell (2012).

The policy variation for the macro tax liability comes mainly from changes in state income taxes; in particular, the state-level EITCs and welfare benefits, which vary across states and over time. The large expansions of the federal EITC, which much of the literature has relied on, are not useful, since the changes affected all states simultaneously and thus would be collinear with time trends. We illustrate this variation by plotting the macro simulated tax liability for high school dropouts for the largest 12 states in panel B of Figure 1.

A potential concern with our identification strategy is that individuals might move to avoid taxes and/or receive higher benefits. However, several papers (e.g., Meyer 2000, Kennan and Walker 2010) suggest that this response is at best modest, particularly for the sample of low-income individuals that are the focus of this study. Thus, while migration responses might be important in other contexts, we do not believe that our estimates will be confounded by them.

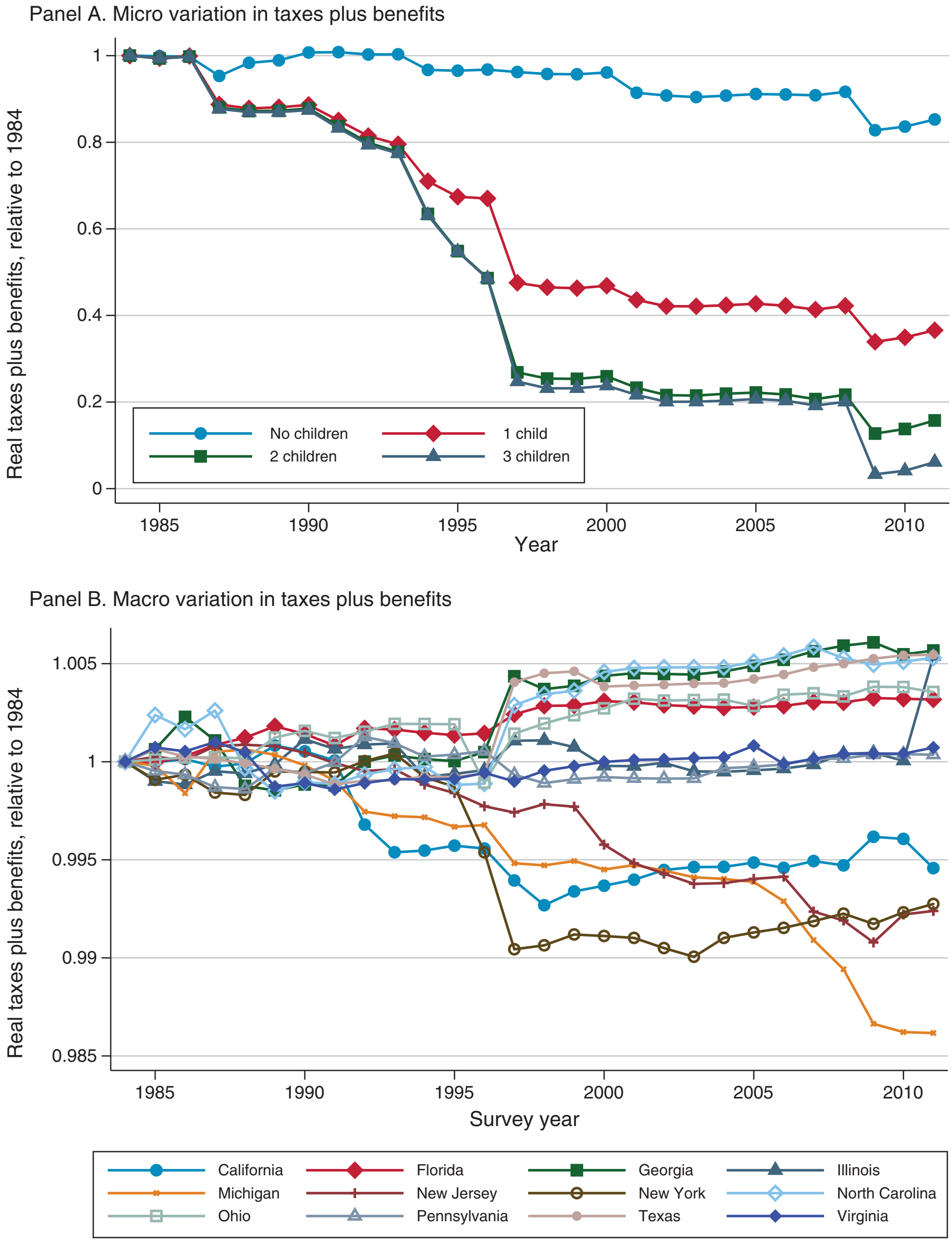

Figure 1. The Variation in Taxes plus Benefits

Notes: Panel A shows the variation in taxes plus benefits for high school dropouts by number of children normalized such that they equal one in 1984. Taxes plus benefits is the net of federal (including EITC), state, and FICA (sum of employer and employee) taxes plus the benefits an individual would be eligible for at no earnings, adjusted for national recipiency rates. Panel B shows residuals from a regression of year fixed effects on the state-level average taxes plus benefits with state means added back to the residual, then normalized such that they equal one in 1984. Taxes plus benefits is the net of federal (including EITC), state, and FICA (sum of employer and employee) taxes plus the benefits an individual would be eligible for at no earnings, adjusted for national recipiency rates.

C. *Empirical Results*

For all of our empirical results, we report IV estimates from a two-stage least squares regression. Reported standard errors in all regressions are clustered on the state level. The notes of the tables contain exact details about the regression specification. All of the OLS results can be found in the online Appendix. Note in interpreting these results that the tax liabilities are in units of $1,000.

The top panel of Table 2 shows the IV estimates for the micro participation (column 1) and employment (column 2) responses to taxes and transfers based on equation (17) above. The results indicate a clear negative and statistically significant participation effect of taxes, consistent with the prior literature. We find that a $1,000 increase in taxes leads to a 3.1 percentage point reduction in the participation probability, which translates to an elasticity of -0.57.[23] We also see fairly similar micro responses for employment.[24]

Our elasticity estimates are well within the range of elasticities that is reported in the literature.[25] This is not that surprising since we use similar variation in taxes to that used in previous literature—in particular, variation driven by the EITC. One notable difference is that past studies typically control for state and year fixed effects, but not their interaction. This yields estimates that confound micro and macro responses (for a discussion of this, see Rothstein 2010). Nevertheless, most of the tax variation in these papers would also have come from across-group variation within labor markets.

The macro participation and employment IV estimates are displayed in the second panel of Table 2. These correspond to empirical estimates from a macro-level (education-state-year cells) two-stage least squares regression of participation and employment rates on market-level tax liabilities, controlling for education $\times$ state and education $\times$ year fixed effects and percent black, percent Hispanic, average age, average age squared, average number of children, and their interactions with education and region-specific time trends. Since the number of observations is much smaller and since there is less variation in tax liabilities across labor markets, the coefficients are estimated less precisely. Nevertheless, there is some suggestive evidence that the macro participation and employment responses are smaller than the micro ones. We show in the online Appendix (Proposition A.2) that such a finding is consistent with a matching model where the bargaining power is lower than the one prescribed by the Hosios condition.

Our results on micro and macro responses to taxation are generally consistent with the meta-analysis conducted in Chetty et al. (2012), which reports slightly

[23] Following the theory, we take the marginal effect and multiply it by the ratio of the income gain from employment over the participation rate. These numbers are all reported in Table 2.

[24] The online Appendix reports the OLS regression results. We see that the OLS participation responses are attenuated relative to our IV estimates. For the full sample, the micro participation elasticity is 0.09 and the macro participation elasticity is -0.8. The micro and macro employment responses are of a similar magnitude. This highlights the importance of instrumenting for the micro and macro tax liabilities. In general, the OLS results are not very informative; for example, there is a strong reverse causality issue where high participation rates will be associated with lower earnings (due to selection) and higher employment taxes. Isolating variation coming from tax policy changes is crucial in order to obtain meaningful results.

[25] Eissa, Kleven, and Kreiner (2008) reports a range of $(-0.35, -1.7)$ with a central elasticity of -0.7.

Table 2—Micro and Macro Responses to Changes in Taxes and Benefits: Instrumental Variable Regressions

Dependant variable	Participation rate: $\hat{\mathcal{K}}_i$ (1)	Employment rate: $\hat{\mathcal{H}}_i$ (2)
Micro response		
Taxes plus benefits	−0.031	−0.029
	(0.002)	(0.002)
Number of observations	1,816,065	1,816,065
Mean of dependent variable	0.81	0.73
Income gain from employment (2010 USD)	15,014	15,014
Tax elasticity	−0.57	−0.60
Macro response: $\partial / \partial T_i$		
Avg. taxes plus benefits within labor market	−0.028	−0.022
	(0.014)	(0.021)
Number of observations	8,568	8,568
Mean of dependent variable	0.79	0.70
Income gain from employment (2010 USD)	13,664	13,664
Tax elasticity	−0.48	−0.42

Notes: Standard errors clustered on state level. The sample is restricted to single women aged 18–55. The data include March CPS for 1984–2011 and ORG for 1994–2010. The first column uses labor force participation as the outcome variable; the second column uses employment status. Taxes plus benefits is the net of federal (including EITC), state, and FICA (sum of employer and employee) taxes plus the benefits an individual would be eligible for at no earnings, adjusted for national recipiency rates. The micro response regressions use individual-level data and include controls for age, age squared, race, ethnicity, and fixed effects for number of children and state × year × month fixed effects, all interacted with education. The macro response regressions use data that are collapsed to the state-year cell; each cell receives equal weight in the regression. Regressions include controls (all interacted with education) for percent black, percent Hispanic, average age, age squared, number of children, fixed effects for state and year, and CPS region time trends.

larger estimates of the extensive steady-state elasticities based on micro evidence than those based on macro evidence. It is worth noting that the macro-based studies cited in Chetty et al. (2012) are based on cross-country evidence that typically comes from a limited number of OECD countries. Nevertheless, it is reassuring to note that our results are similar, based on a panel data approach across all states, over time, in the United States.

A concern with our macro estimates, which are identified by state-year variation in tax liabilities, is that they may be confounded by policy endogeneity. In particular, states may endogenously set taxes and welfare benefits based on prevailing local economic conditions. Our baseline estimates control for region-specific time trends, which should partially address this issue. To further explore the robustness of our estimates, we consider several alternative specifications and report the results in Table 3. Table 3 provides a series of robustness tests. The first column reports our baseline estimates for comparison. In columns 2–4, we drop the region-specific time trends from the regressions and include alternative controls for pretrends. Since the micro participation regressions control for year × state fixed effects, these are not affected (panel A), but panels B and C show that the macro responses are very robust to controlling for division × year fixed effects, region × year fixed effects, and no

Table 3—Alternative Estimates of Participation and Employment Responses

	Region time trend (1)	Div. × year FE (2)	Reg. × year FE (3)	No pretrends (4)	No state taxes (5)	State unempl. (6)	Full take up (7)
Panel A. Micro participation response							
Taxes plus benefits	−0.031	−0.031	−0.031	−0.031	−0.034	−0.032	−0.018
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)
Number of observations	1,816,065	1,816,065	1,816,065	1,816,065	1,816,065	1,816,065	1,816,065
Mean of dependent variable	0.81	0.81	0.81	0.81	0.81	0.81	0.81
Income gain from empl.	15,014	15,014	15,014	15,014	14,501	15,014	15,475
Tax elasticity	−0.57	−0.57	−0.57	−0.57	−0.61	−0.57	−0.36
Panel B. Macro participation response							
Avg. taxes plus benefits within labor market	−0.028	−0.030	−0.031	−0.034	−0.028	−0.031	−0.009
	(0.014)	(0.018)	(0.015)	(0.016)	(0.022)	(0.013)	(0.006)
Number of observations	8,568	8,568	8,568	8,568	8,568	8,568	8,568
Mean of dependent variable	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Income gain from empl.	13,664	13,664	13,664	13,664	12,695	13,664	13,914
Tax elasticity	−0.48	−0.51	−0.52	−0.53	−0.48	−0.52	−0.13
Panel C. Macro employment response							
Avg. taxes plus benefits within labor market	−0.022	−0.023	−0.021	−0.032	−0.034	−0.030	−0.010
	(0.021)	(0.022)	(0.020)	(0.019)	(0.022)	(0.015)	(0.009)
Number of observations	8,568	8,568	8,568	8,568	8,568	8,568	8,568
Mean of dependent variable	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Income gain from empl.	13,664	13,664	13,664	13,664	13,664	12,479	13,914
Tax elasticity	−0.42	−0.43	−0.41	−0.52	−0.53	−0.49	−0.20

Notes: Standard errors clustered on state level. The sample is restricted to single men and women aged 18–55. The data include March CPS for 1984–2011 and ORG for 1994–2010. Our baseline specification from Table 3 is contained in column 1. Column 2 replaces region-specific linear time trends with division × year fixed effects. Column 3 replaces region-specific linear time trends with region × year fixed effects. Column 4 drops region-specific linear time trends. Column 5 is our baseline specification but drops state taxes, including state EITC supplements, from both the OLS and IV tax liabilities. Taxes plus benefits is the net of federal (including EITC), state, and FICA (sum of employer and employee) taxes plus the benefits an individual would be eligible for at no earnings, adjusted for national recipiency rates. Column 6 controls for the state unemployment rate interacted with education. Column 7 is our baseline specification but assumes 100 percent take-up rates for AFDC/TANF and food stamps for the computation of the imputed tax liability and the simulated instrument.

controls for pretrends. In column 5, we present our results dropping state taxes (state EITC and state income taxes) from our imputed tax liability and instrument, given that those may be endogenous, as Hoynes and Patel (2015) have argued. While this slightly reduces the precision of our macro estimates, the results are qualitatively similar. Finally, column 6 controls for the state unemployment rate interacted with education as a proxy for the state-specific economic environment and shows a very similar pattern. Overall, the robustness of our estimates suggests that policy endogeneity is not of first-order importance in our setting.[26]

[26] In column 7, we show our results when we calculate tax liabilities assuming that all individuals who would be eligible to receive AFDC, TANF, or food stamps on the basis of their income actually take up benefits. Since this leads to larger calculated tax liabilities (and values for the instruments), the estimated marginal effects and elasticities are reduced, but the result that macro participation responses are larger than micro participation responses is actually more pronounced.

Finally, Table 4 considers behavioral responses over the business cycle. In particular, this allows us to test whether spillovers are larger in recessions, as some recent research has found. We rely on several proxies for the business cycle: the 6-month change in the unemployment rate, the state unemployment rate, and an indicator for whether the unemployment rate exceeds 9 percent. Across all specifications, we see that micro and macro participation and employment responses tend to be lower when the unemployment rate is relatively high. This is consistent with results in Schmieder, von Wachter, and Bender (2012) and Kroft and Notowidigdo (2016). There is also some suggestive evidence that the micro-macro participation gap increases in weak labor markets; for instance, for the 6-month change in unemployment specification, the gap is roughly 0.01 in weak labor markets but only 0.002 in strong labor markets. We emphasize, however, that lack of precision limits any strong conclusion about how the gap varies over the cycle.

Overall, these results suggest that while micro labor supply responses are sizable and in line with what the literature has found before, they may not always be good approximations for the macro employment responses. In particular, our evidence broadly suggests that macro responses tend to be lower than micro responses. Although this is some of the first evidence on the gap between micro and macro elasticities, it is however worth noting that our macro estimates are less precisely estimated than our micro ones. Such discrepancy can easily be explained by the limited policy variations at the state level over time, compared with policy variations across individuals with different numbers of kids over time. Future research should use other sources of policy variations as robustness checks for our macro estimates.

III. Simulating the Optimal Tax Schedule

In this section we show how unemployment and wage responses affect the shape of the optimal tax-and-transfer schedule. For this purpose we simulate the optimal tax schedule using the sufficient statistics formula for the optimal tax-and-transfer schedule in the mixed model (see Proposition 3).[27] We calibrate the formula partially relying on the empirical estimates from the previous section and partially relying on parameter estimates from the previous literature. Since there is considerable uncertainty about most of these parameters, these simulations are very stylized and should be viewed as an illustration of the comparative statics of our optimal tax formula, rather than a precise attempt to derive the optimal tax schedule for any particular population.[28]

To simulate the optimal tax schedule, we solve the system of first-order conditions derived in the theoretical section for the tax schedule at different income levels. The system consists of $I+2$ unknowns: the $i = 0, \ldots, I$ tax levels T_i as well as the Lagrange multiplier λ. These are identified by $I+2$ equations: the I

[27] We thank Emmanuel Saez for sharing his code.

[28] Such an exercise for the United States would, for example, have to take into account that policymakers seem to have placed different welfare weights on different groups of single individuals, depending on the number of children. Backing out the implicit welfare weights in the current tax schedule given an optimal tax framework and calibrating how the tax schedule given these welfare weights would change under alternative models would be interesting but is beyond the scope of this paper.

Table 4—Participation and Employment Responses: Heterogeneous Labor Market Conditions

	Regression coefficients		Extrapolated marginal effects	
	Marginal effect of tax liability (1)	Interaction of tax liability with labor market meas. (2)	Weak labor market (3)	Strong labor market (4)
Panel A. Micro participation				
6-month change in unempl.	−0.031	0.0011	−0.030	−0.033
	(0.002)	(0.0004)		
State unempl. rate	−0.032	0.0012	−0.027	−0.036
	(0.002)	(0.0003)		
Unempl. above 9 percent	−0.032	0.0054	−0.026	−0.032
	(0.002)	(0.0013)		
Panel B. Macro participation				
6-month change in unempl.	−0.028	0.0046	−0.022	−0.035
	(0.015)	(0.0028)		
State unempl. rate	−0.031	0.0011	−0.026	−0.036
	(0.017)	(0.0012)		
Unempl. above 9 percent	−0.030	0.0090	−0.021	−0.030
	(0.016)	(0.0052)		
Panel C. Micro employment				
6-month change in unempl.	−0.029	0.0007	−0.028	−0.030
	(0.002)	(0.0005)		
State unempl. rate	−0.029	0.0015	−0.024	−0.035
	(0.002)	(0.0003)		
Unempl. above 9 percent	−0.029	0.0074	−0.022	−0.029
	(0.002)	(0.0018)		
Panel D. Macro employment				
6-month change in unempl.	−0.022	0.0030	−0.018	−0.025
	(0.018)	(0.0031)		
State unempl. rate	−0.029	0.0018	−0.021	−0.036
	(0.018)	(0.0013)		
Unempl. above 9 percent	−0.028	0.0112	−0.018	−0.029
	(0.016)	(0.0060)		

Notes: Standard errors clustered on state level. The micro response regressions use individual-level data and include controls for age, age squared, race, ethnicity, and fixed effects for number of children and state × year × month. The macro response regressions use data that are collapsed to the state-year cell observations; each cell receives equal weight in the regression. Regressions include controls for percent black, percent Hispanic, average age, age squared, number of children, fixed effects for state and year, and CPS region time trends. Weak and strong labor market marginal effects assume the market indicator is two standard deviations above or below the mean for the continuous variables.

first-order conditions (15); the government budget constraint (1); and, finally, the normalization $\sum_i h_i \, g_i = 1$, which holds in the absence of income effects.[29] We base our simulation on the empirical income distribution for single workers in the March 2011 CPS, which we discretize into a grid of bins of \$500 width. Following

[29] Alternatively, one could also use the FOC for benefit levels derived in Appendix A which holds in the presence of income effects.

Saez (2002),we parameterize g_i using the functional form: $g_i = 1/\left(\lambda\left(w_i - T_i\right)^{\nu}\right)$, where ν is the parameter describing society's preferences for redistribution. We set $\nu = 0.5$ as our baseline, which corresponds to moderate distributive preferences. Below we will see that this leads to optimal tax schedules similar to the observed schedules and thus may be a good approximation of the preferences underlying US tax policy, but we also show how the optimal tax schedule changes under alternative ν. We also follow Saez (2002) in our specification for the earnings distribution functions $h_i(T)$ and in setting the external revenue requirement of the government E. See the Appendix for additional details.

In order to simulate equation (15), we need to specify the following four sets of behavioral parameters: the intensive margin mobility elasticity ζ_i, the extensive margin employment elasticity η_i, the employment-enhancing effect of taxation μ_i, and the matrix ratio of the macro and micro participation responses in equation (16). The intensive margin mobility elasticity ζ_i can be directly mapped into the classical intensive earnings elasticity ε_i using the formula $\zeta_i = \left(w_i/(w_i - w_{i-1})\right)\varepsilon_i$.[30] Based on the prior literature, a reasonable range for the intensive margin employment elasticity is 0.2–0.3 (e.g., Chetty, Friedman, Olsen, and Pistaferri 2011; Chetty, Friedman, and Saez 2013). We therefore set $\varepsilon_i = 0.25$ for all i.[31] For the extensive margin elasticity, we follow Saez (2002) and set $\eta = 0$ for incomes higher than \$20,000. For incomes lower than \$20,000, we use our empirical estimates from the previous section.

The two key new parameters in our tax formula are μ_i and the matrix ratio of the macro and micro participation responses. Except for two papers (Manning 1993; Lehmann et al. 2016) that suggest a positive μ_i, we are not aware of empirical estimates of μ_i. We therefore set $\mu_i = 0$ for all i in our baseline and show simulations for a range of possible values for μ_i. For the matrix ratio, we start with the case that the matrix ratio is equal to the identity matrix, which corresponds to a situation where micro and macro responses are identical. We then contrast this with a situation where the matrix ratio is still a diagonal matrix, but with diagonal elements different from zero. In particular, we use our empirical estimates from the previous section of the macro and micro participation response to calibrate these diagonal elements. This is a practical simplification, as in principle there is no reason to believe that once macro and micro responses are different the resulting matrix ratio remains diagonal. It is a useful starting point given that this is a relatively straightforward departure from the classic case of equal responses that the prior literature has assumed. In general, we believe that estimating macro and micro responses on the intensive margin is a fruitful avenue for future research.

Figure 2 shows the optimal tax-and-transfer schedule for incomes below \$20,000, and Table 5 provides additional details for these simulations. In Figure 2, panel A shows post-tax income plotted against pretax income, and panel B depicts the corresponding marginal tax rate as a function of pretax income. We begin with the case where $\mu_i = 0$, and macro and micro participation responses are equal, which thus

[30] See the appendix of Saez (2002).

[31] In the online Appendix, we also show simulations for $\varepsilon = 0.5$ for low-income workers with qualitatively similar results.

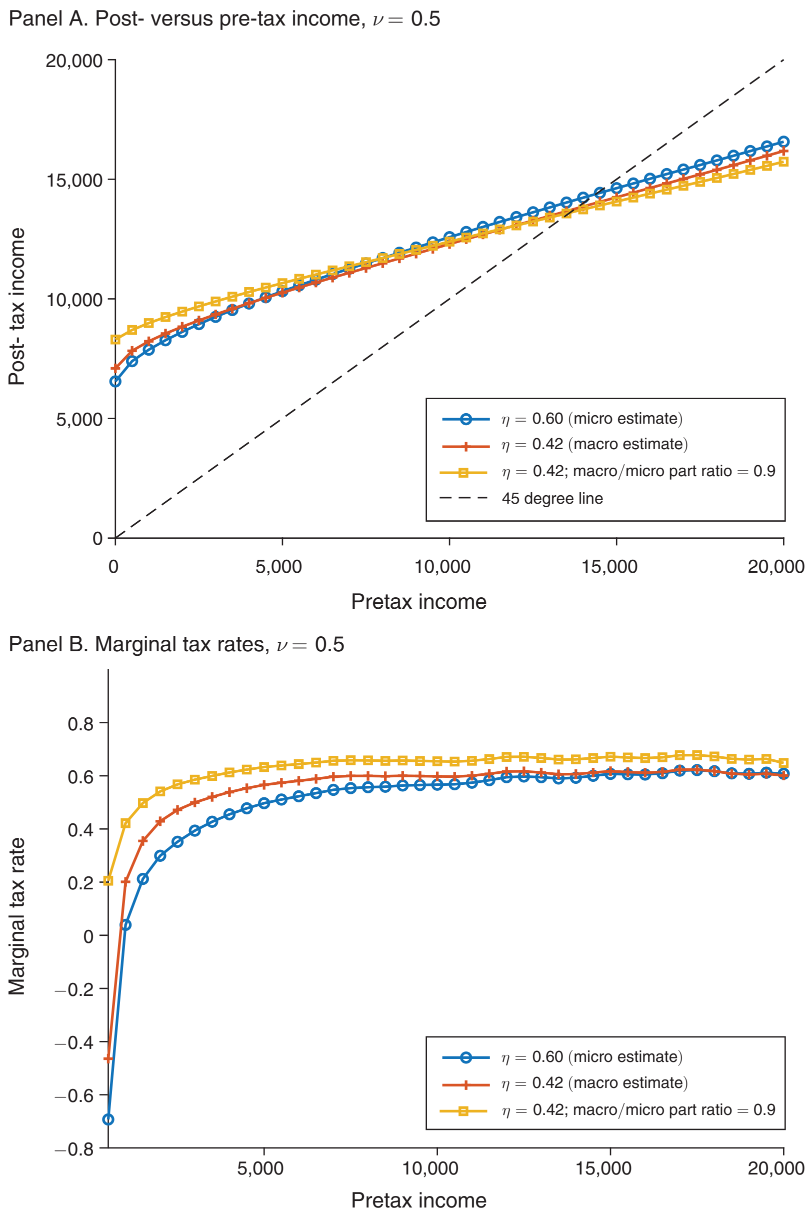

Figure 2. Optimal Tax-and-Transfer Schedule: Baseline

Notes: Simulations of the optimal tax-and-transfer schedule under alternate assumptions on employment and participation responses using equation (15) in the paper. All simulations assume that the intensive margin elasticity $\varepsilon = 0.25$ at all income levels and that the employment-enhancing effect of taxation $\mu = 0$ at all income levels. The first two lines (blue with circle and red with plus signs) assume that the macro/micro participation response ratio is equal to 1 and sets the extensive margin employment elasticity to 0.6 and 0.42, respectively. The yellow line with stars sets $\eta = 0.42$ and the macro-micro participation response ratio equal to the empirical estimate of 0.9. In panel B, the first dot of each line is the employment tax rate of moving from 0 income to the first income bin. Incomes are specified in dollars.

TABLE 5—SIMULATING THE OPTIMAL TAX-AND-TRANSFER SCHEDULE: $\nu = 0.50$

	η	μ	$\frac{\frac{dK}{dT}}{\frac{dK}{dT}\vert_{\text{Micro}}}$	Demogrant b	Empl. tax $T_1 + b$	ATR (6k-0)	Avg. MTR	Break-even $T(w) = 0$
Panel A. Alternative η, macro–micro ratio = 1, $\mu = 0$								
	0.01	0.00	1.00	9,300	500	84.89	0.56	11,900
Macro estimate	0.42	0.00	1.00	7,100	−200	40.21	0.51	13,800
Micro estimate	0.60	0.00	1.00	6,500	−300	29.11	0.50	14,400
	1.00	0.00	1.00	5,600	−400	14.10	0.46	15,500
Panel B. Comparing different macro–micro participation ratios								
	0.42	0.00	0.75	9,700	300	69.01	0.62	13,500
Benchmark	0.42	0.00	0.90	8,300	100	54.75	0.56	13,600
	0.42	0.00	1.00	7,100	−200	40.21	0.51	13,800
	0.42	0.00	1.25	3,200	−3,200	−17.71	0.44	14,500
Panel C. Comparing different values for μ								
	0.42	0.00	1.00	7,100	−200	40.21	0.51	13,800
	0.42	0.10	1.00	8,000	−300	32.98	0.57	15,700
	0.42	0.20	1.00	9,100	−300	24.57	0.63	17,900
	0.42	0.30	1.00	10,400	−300	15.52	0.72	20,500
Panel D. Optimal tax schedule over business cycle with wage and unemployment responses								
Recession	0.34	0.00	0.73	10,100	300	74.49	0.63	13,400
Normal	0.42	0.00	0.90	8,300	100	54.75	0.56	13,600
Boom	0.48	0.00	1.06	6,000	−700	24.30	0.48	14,100
Panel E. Optimal tax schedule over business cycle without wage and unemployment responses								
Recession	0.34	0.00	1.00	7,400	−100	46.12	0.52	13,500
Normal	0.42	0.00	1.00	7,100	−200	40.21	0.51	13,800
Boom	0.48	0.00	1.00	6,900	−300	36.30	0.51	14,000

Notes: The table shows simulations of the optimal tax schedule based on equation (15) in the text. All simulations are based on the single-worker earnings distribution in the March 2011 CPS and assume the parameter values $\nu = 0.50$; $\varepsilon = 0.25$; and, for wages above \$20,000, $\eta = 0$. In panel D, both η and the macro–micro ratio vary between boom and recession, while in panel E the macro–micro ratio is held constant at 1. ATR (6k-0) stands for the mean of Average Tax Rates for taxpayers who earn between \$0 and \$6,000. MTR stands for Marginal Tax Rates.

corresponds exactly to the formula in Saez (2002). The line with circles shows the simulated schedule when we set η_i to our estimate for the micro extensive employment elasticity of 0.6 from Table 2. A key takeaway from our theoretical analysis is that the employment effects should really be measured on the macro level, and thus we contrast this scenario to the line with plus signs to highlight the effect of moving to macro estimates where $\eta_i = 0.42$, consistent with our estimate in Table 2. This moderately increases the benefit for the nonemployed b from \$6,500 to \$7,100. Keeping η_i at the macro estimate level, we then use our empirical estimates for the macro and micro participation responses to calibrate the macro–micro matrix ratio to be the diagonal matrix with $0.9 \simeq -0.028/-0.031$ as the element on the diagonal. The resulting tax schedule (shown with squares) now features a substantially higher benefit to the nonemployed of \$8,300 and higher marginal tax rates at the bottom. Panel B of Figure 2 shows the corresponding marginal tax rates at each income level. This figure highlights the result in Jacquet, Lehmann, and Van der Linden (2013) that even with large extensive responses, the marginal tax rate at positive incomes is always positive, while there is a discontinuity at 0 where the optimal tax schedule may feature a negative employment tax corresponding to $T_1 + b < 0$. Interestingly, this figure suggests that for these benchmark parameters, the optimal tax schedule

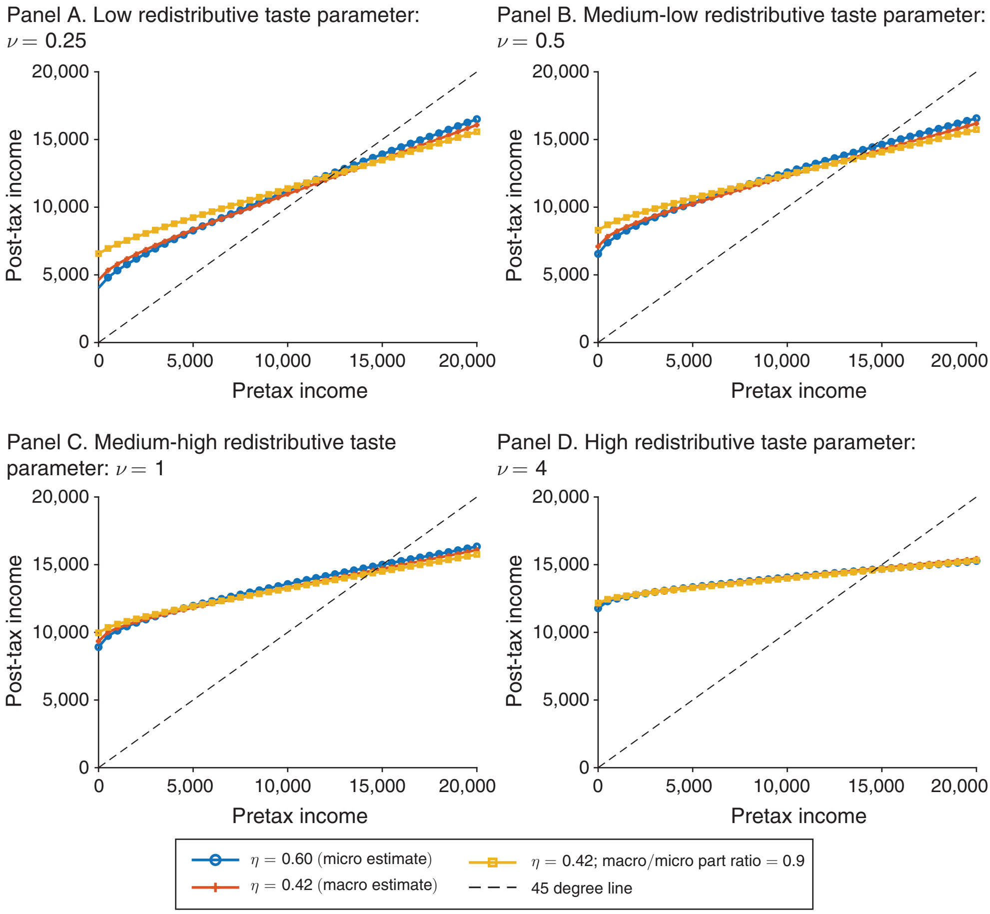

Figure 3. Optimal Tax-and-Transfer Schedule under Alternative Redistributive Preferences

Notes: Simulations of the optimal tax-and-transfer schedule using equation (15) in the paper. The simulations correspond to Figure 2, but each panel uses different redistributive taste parameters ν. All simulations assume $\varepsilon = 0.25$, $\eta_{low} = 0.42$, $\eta_{high} = 0$, and $\mu = 0$. Incomes are specified in dollars.

features an EITC-like structure with a negative employment tax $(T_1 + b < 0)$ only as long as we do not take into account the wage and unemployment spillover effects as measured by our (admittedly noisy) gap between macro and micro participation responses.

In Figure 3, we show the same comparisons but for a wide range of redistributive tastes of the social planner $(\nu = 0.25, 0.5, 1, 4)$. The figure highlights that taking into account endogenous wages and unemployment via the macro–micro participation ratio is much more relevant to the shape of the optimal tax schedule for lower values of the redistributive taste parameter, such as $\nu = 0.25$ or $\nu = 0.5$. For higher values of ν, our optimal tax formula produces relatively similar results as the Saez (2002) formula. The intuition for this is that our formula essentially rescales the social welfare weights g_i for positive income levels, thus putting more weight at the bottom (equation (16)). For high ν, the social planner already exhibits

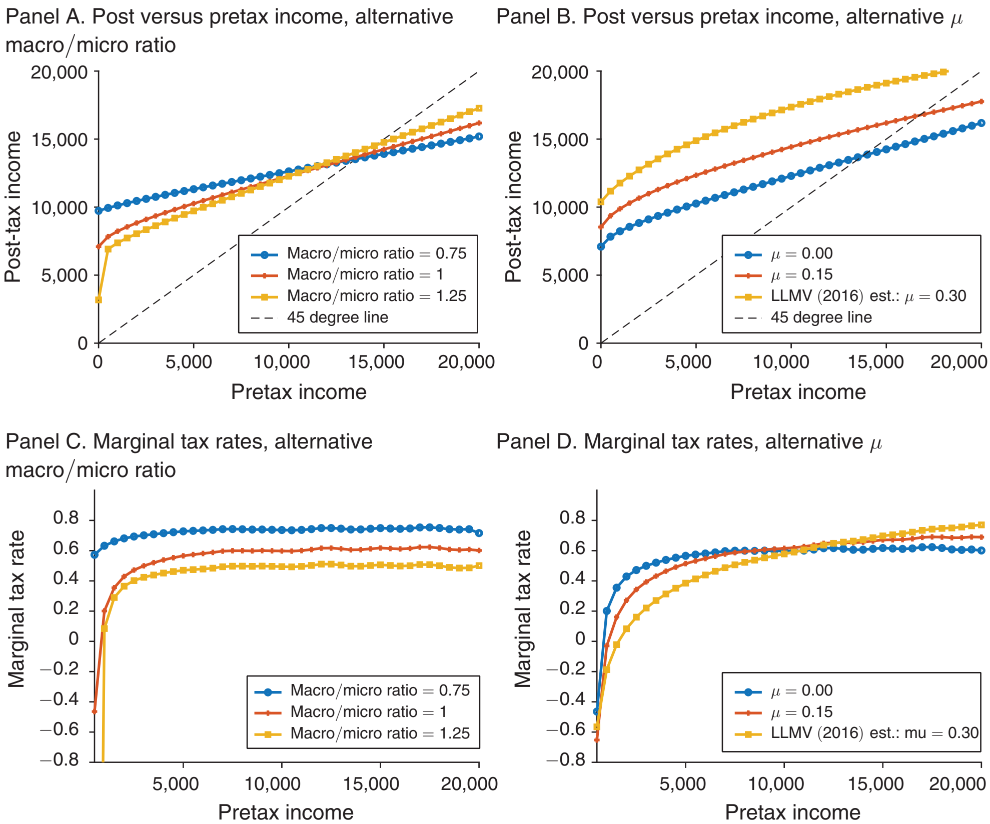

Figure 4. The Effect of the Macro/Micro Participation Ratio and μ on the Optimal Tax-and-Transfer Schedule

Notes: Simulations of the optimal tax-and-transfer schedule using equation (15) in the paper. Panels A and C contrast the optimal tax-and-transfer schedule under different values for the macro/micro participation response ratio while setting $\mu = 0$. Panels B and D contrast the optimal schedule for different values of μ while setting the macro/micro participation response ratio to 1. All simulations assume $\varepsilon = 0.25$, $\eta_{low} = 0.42$, $\eta_{high} = 0$, and the redistributive taste parameter $\nu = 0.5$. In panels C and D, the first dot of each line is the employment tax rate of moving from 0 income to the first income bin. Incomes are specified in dollars. LLMV refers to Lehmann, Lucifora, Moriconi, and Van der Liden (2016).

essentially Rawlsian preferences and is simply constrained by employment responses to set what is close to the revenue-maximizing tax schedule.[32]

Given the considerable uncertainty regarding the macro to micro participation ratio and the value for μ_i, Figure 4 shows comparative statics from our benchmark schedule when varying the macro–micro ratio and μ_i, which we assume to be constant across income groups. Panel A shows the tax schedule, setting the ratio to 0.75, 1, and 1.25. For this range we find substantial differences in the benefit b, ranging from \$9,700 with a low ratio to only \$3,200 if the ratio is equal to 1.25. In the latter

[32] The online Appendix provides all simulations from this section for these alternative values for ν as well.

case, the optimal tax also features a substantial employment credit at the bottom (see panel C). Panels B and D show the tax schedules for alternative values of μ_i. Higher values of μ_i increase the demogrant, and transfers at lower incomes become much larger and shift the break-even point (of zero tax liability) further to the right. This in turn is financed by substantially higher marginal tax rates at higher income levels. For example, using a value of $\mu = 0.3$, which corresponds to the empirical estimate in Lehmann et al. (2016), the simulations imply a demogrant of \$10,400 and an average marginal tax rate of 72 percent. The intuition for this is straightforward: a positive μ_i implies that higher marginal tax rates have an employment-enhancing effect by pulling people from zero income into the labor force, thus raising new revenue and counteracting the usual intensive margin response that would reduce tax revenue whenever employment tax is positive. The potentially large impact of μ_i on the optimal tax rate and the comparatively sparse empirical literature on this suggest that additional empirical estimates of this parameter would be highly valuable.

Other papers have stressed the possibility that macro employment responses could be significantly lower than micro employment responses, particularly in the context of unemployment insurance and job search assistance. This has typically been explained with the possibility of job rationing, which may manifest especially during recessions. Our estimates in Table 4, while noisy, are consistent with this view: while both macro and micro responses decline in recessions, the decline is much larger for macro responses, with respect to both employment and participation. The business cycle macro estimates suggest that spillover effects could be larger during economic downturns. Figure 5 simulates how the optimal tax schedule would vary over the business cycle given our estimates from Table 4. We present results from the estimates based on the 6-month change in the unemployment rate, but using the other measures yields qualitatively very similar results. In panels A and C of Figure 5, we show the optimal tax schedule for different business cycle states implied by our optimal tax formula. The transfer at zero income is around \$5,700 during a strong labor market with a large employment credit at the bottom and relatively low marginal tax rates. During weak labor markets, the simulation suggests that the transfer at zero should increase to \$10,500 per year with much higher marginal tax rates. In contrast, panels B and D of Figure 5 show the tax schedule implied by the Saez (2002) formula calibrating η to the macro employment effects estimated over the business cycle.[33] While the decline in macro employment responses during weak labor markets also leads to an increase in transfers at the bottom and a slight increase in employment tax rates, the difference relative to a boom is only around \$500 due to the absence of the spillover channel.

IV. Conclusion

This paper revisits the debate about the desirability of the EITC versus the NIT. We have shown that whether the optimal employment tax on the working poor is positive or negative depends on the presence of unemployment and wage responses

[33] Using the micro employment effects yields even less variation in the optimal tax schedule over the cycle.

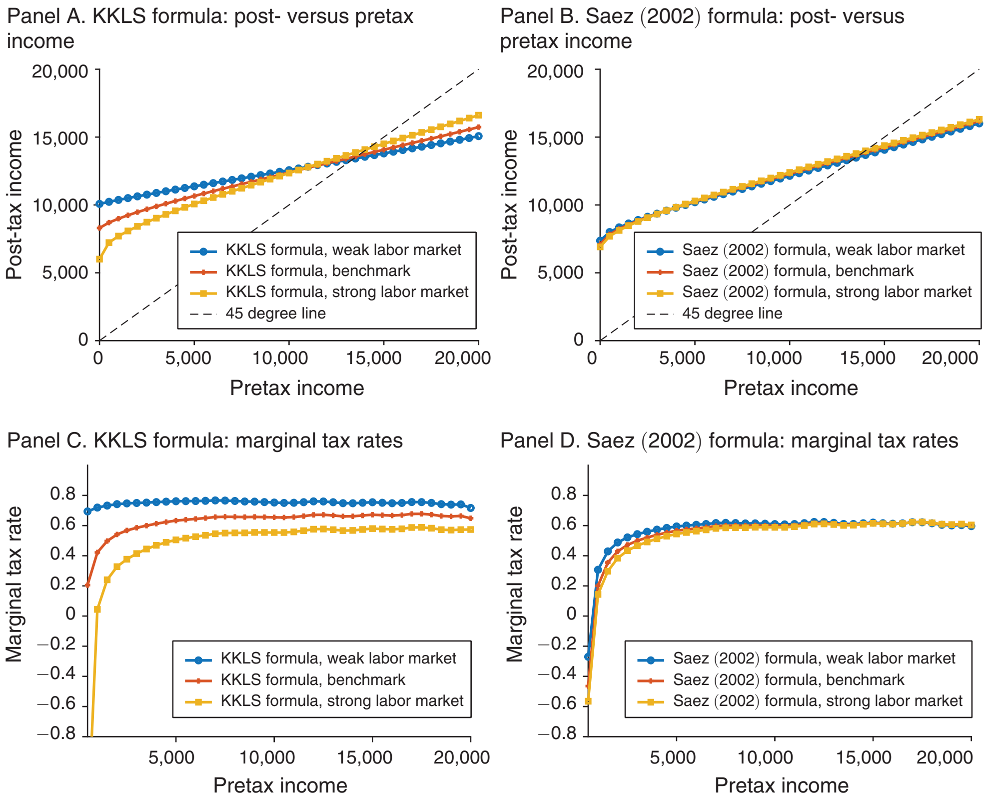

Figure 5. Optimal Tax-and-Transfer Schedule in Weak versus Strong Labor Markets

Notes: Simulations of the optimal tax-and-transfer schedule using equation (15) in the paper. Panels A and C contrast the optimal tax-and-transfer schedule during weak and strong labor markets using the empirical estimates in the paper. Panels A and C use the optimal tax formula in the paper (designated KKLS formula) where both the employment elasticity η_{low} and the macro/micro participation response vary between booms and recessions. Panels B and D set the macro/micro participation response ratio to 1 and let only the employment elasticity vary over the cycle, and they thus correspond to the Saez (2002) formula. The solid line shows the tax schedule using the weak labor market estimates from Table 4 based on the 6-month change in the unemployment rate. The line with plus signs shows the tax schedule for the corresponding strong labor market estimates from Table 4. All simulations assume $\varepsilon = 0.25$, $\eta_{high} = 0$, $\mu = 0$, and the redistributive taste parameter $\nu = 0.5$. In panels C and D, the first dot of each line is the employment tax rate of moving from 0 income to the first income bin. All tax values are in US$.

to taxation. Our sufficient statistics optimal tax formula, combined with our reduced-form empirical estimates, indicates that the optimal policy is pushed more toward an NIT than the standard optimal tax model would suggest, although statistical precision limits strong conclusions about the magnitude of the macro responses.

There are several limitations to our analysis that should be addressed in future work. First, there is clearly a need for better empirical estimates of the macro effects of taxation. Most studies of macro labor supply responses rely on cross-country variation in taxes, which can be substantial. While this variation is clearly desirable for efficiency reasons, tastes across countries for redistribution and other forms of government spending are probably correlated with taxes and employment and are difficult to fully control for. What is needed is reliable policy variation in taxes across labor markets, similar to the variation in unemployment insurance benefit payments that is exploited in Lalive, Landais, and Zweimüller (2015). Second, it would be very interesting to get better estimates of the wage-moderating effects of tax progressivity. Third, it would be worthwhile to study business cycle effects of taxation more directly by introducing dynamics into the model. The approach we adopted in this paper is entirely steady state. Finally, it would be useful to develop a model that more fully integrates unemployment insurance benefits and income taxes, where benefits depend on prior wages, as is currently the policy in most developed economies.

Appendix A. Optimal Benefit Level

The optimal condition with respect to the benefit level is obtained from differentiating (8) with respect to b:

$$\frac{\partial \Lambda}{\partial b} = -1 + \sum_{i=1}^{I} h_i + \sum_{i=1}^{I} (T_i + b) \frac{\partial \mathcal{H}_i}{\partial b} + \frac{u'(b)}{\lambda} \frac{\partial \Omega}{\partial U_0} + \sum_{i=1}^{I} \frac{1}{\lambda} \frac{\partial \Omega}{\partial U_i} \frac{\partial \mathcal{U}_i}{\partial b}.$$

Differentiating $\mathcal{U}_i(\mathbf{t}) \equiv \mathcal{P}_i(\mathbf{t}) u(\mathcal{C}_i(\mathbf{t})) + (1 - \mathcal{P}_i(\mathbf{t})) u(b)$ with respect to b gives

$$\frac{\partial \mathcal{U}_i}{\partial b} = (1 - p_i) u'(b) + p_i u'(c_i) \left[\frac{\partial \mathcal{C}_i}{\partial b} + \frac{\partial \mathcal{P}_i}{\partial b} \frac{u(c_i) - u(b)}{p_i u'(c_i)} \right].$$

Using $h_0 = 1 - \sum_{i=1}^{I} h_i$ leads to:

$$\text{(A1)} \quad \frac{\partial \Lambda}{\partial b} = -h_0 + \sum_{i=1}^{I} (T_i + b) \frac{\partial \mathcal{H}_i}{\partial b} + g_0 h_0 + \sum_{i=1}^{I} g_i h_i \left[\frac{\partial \mathcal{C}_i}{\partial b} + \frac{\partial \mathcal{P}_i}{\partial b} \frac{u(c_i) - u(b)}{p_i u'(c_i)} \right],$$

where the social marginal welfare weight on the nonemployed is

$$\text{(A2)} \quad g_0 \equiv \frac{u'(b)}{\lambda h_0} \left[\frac{\partial \Omega}{\partial U_0} + \sum_{i=1}^{I} (1 - p_i) \frac{\partial \Omega}{\partial U_i} \right].$$

We now show how (A1) can be simplified if we assume income effects away. In the absence of income effects, a simultaneous change in all tax liabilities and welfare benefit $\Delta T_1 = \cdots = \Delta T_i = -\Delta b$ induces no changes in wages, conditional employment probabilities, or employment levels, so that $\sum_{j=1}^{I} \partial \mathcal{W}_i / \partial T_j = \partial \mathcal{W}_i / \partial b$, $\sum_{j=1}^{I} \partial \mathcal{P}_i / \partial T_j = \partial \mathcal{P}_i / \partial b$, and $\sum_{j=1}^{I} \partial \mathcal{H}_i / \partial T_j = \partial \mathcal{H}_i / \partial b$. Using equations (4) and (5), equation (10) can be rewritten as:

$$\text{(A3)} \quad 0 = h_j + \sum_{i=1}^{I} (T_i + b) \frac{\partial \mathcal{H}_i}{\partial T_j} + \sum_{i=1}^{I} g_i h_i \left[\frac{\partial \mathcal{C}_i}{\partial T_j} + \frac{\partial \mathcal{P}_i}{\partial T_j} \frac{u(c_i) - u(b)}{p_i u'(c_i)} \right].$$

Using that $\partial \mathcal{C}_i/\partial T_i = (\partial \mathcal{W}_i/\partial T_i) - 1$ and for $j \neq i$, $\partial \mathcal{C}_i/\partial T_j = \partial \mathcal{W}_i/\partial T_j$, summing (A3) for all $j \in \{1,\ldots,I\}$ and subtracting this sum by $\partial \Lambda/\partial b = 0$ in equation (A1) leads to

$$0 = \sum_{i=0}^{I} h_i + \sum_{i=1}^{I}(T_i+b)\left(\sum_{j=1}^{I}\frac{\partial \mathcal{H}_i}{\partial T_j} - \frac{\partial \mathcal{H}_i}{\partial b}\right) - \left(g_0 h_0 + \sum_{i=1}^{I} g_i h_i\right) + \sum_{i=1}^{I} g_i h_i\left(\sum_{j=1}^{I}\frac{\partial \mathcal{W}_i}{\partial T_j} - \frac{\partial \mathcal{W}_i}{\partial b}\right) + \sum_{i=1}^{I} g_i h_i \frac{u(c_i)-u(b)}{u'(c_i)}\left(\sum_{j=1}^{I}\frac{\partial \mathcal{P}_i}{\partial T_j} - \frac{\partial \mathcal{P}_i}{\partial b}\right). \tag{A4}$$

In the absence of income effects, (A4) can be simplified to

$$g_0 h_0 + \sum_{i=1}^{I} g_i h_i = \sum_{i=0}^{I} h_i = 1.$$

Appendix B. Derivation of Equation (15)

Using equation (16), equation (11) can be rewritten as

$$\mathbf{0} = \mathbf{h} + \frac{\mathbf{d}\mathcal{H}}{\mathbf{dT}} \cdot (\mathbf{T} + \mathbf{b}) - (\hat{g}_1 h_1, \ldots, \hat{g}_I h_I)^T.$$

That is, for each $j = 1, \ldots, I$, as

$$0 = (1 - \hat{g}_j)\, h_j + \sum_{i=1}^{I} (T_i + b)\frac{\partial \mathcal{H}_i}{\partial T_j}.$$

Using (14a), we get

$$\begin{aligned}(1-\hat{g}_j)\,h_j &= -(T_{j-1}+b)\frac{\partial \mathcal{H}_{j-1}}{\partial T_j} - (T_j+b)\frac{\partial \mathcal{H}_j}{\partial T_j} - (T_{j+1}+b)\frac{\partial \mathcal{H}_{j+1}}{\partial T_j} \\ &= -(T_{j-1}+b)\frac{\partial \tilde{\mathcal{H}}_{j-1}}{\partial (T_j - T_{j-1})} \\ &\quad - (T_j+b)\left[\frac{\partial \tilde{\mathcal{H}}_j}{\partial (T_j - T_{j-1})} + \frac{\partial \tilde{\mathcal{H}}_j}{\partial T_j} - \frac{\partial \tilde{\mathcal{H}}_j}{\partial T_{j+1} - T_j}\right] \\ &\quad + (T_{j+1}+b)\frac{\partial \tilde{\mathcal{H}}_{j+1}}{\partial T_{j+1} - T_j}.\end{aligned}$$

And so, using (14d),

$$\left(1 - \hat{g}_j - \frac{T_j + b}{c_j - b}\eta_j\right) h_j = -\left[(T_{j-1}+b)\frac{\partial \tilde{\mathcal{H}}_{j-1}}{\partial (T_j - T_{j-1})} + (T_j + b)\frac{\partial \tilde{\mathcal{H}}_j}{\partial (T_j - T_{j-1})}\right] + \left[(T_j+b)\frac{\partial \tilde{\mathcal{H}}_j}{\partial (T_{j+1} - T_j)} + (T_{j+1}+b)\frac{\partial \tilde{\mathcal{H}}_{j+1}}{\partial (T_{j+1} - T_j)}\right].$$

Summing the latter equality for $j = i, \ldots, I$ leads to

$$-\left[\left(T_{i-1}+b\right)\frac{\partial\tilde{\mathcal{H}}_{i-1}}{\partial\left(T_i-T_{i-1}\right)}+\left(T_i+b\right)\frac{\partial\tilde{\mathcal{H}}_i}{\partial\left(T_i-T_{i-1}\right)}\right] = \sum_{i=j}^{I}\left(1-\hat{g}_j-\frac{T_j+b}{c_j-b}\eta_j\right)h_j.$$

Combining the latter equation with

$$-\left[\left(T_{i-1}+b\right)\frac{\partial\tilde{\mathcal{H}}_{i-1}}{\partial\left(T_i-T_{i-1}\right)}+\left(T_i+b\right)\frac{\partial\tilde{\mathcal{H}}_i}{\partial\left(T_i-T_{i-1}\right)}\right]$$

$$= -\left(T_i-T_{i-1}\right)\frac{\partial\tilde{\mathcal{H}}_i}{\partial\left(T_i-T_{i-1}\right)}-\left(T_{i-1}+b\right)\left[\frac{\partial\tilde{\mathcal{H}}_{i-1}}{\partial\left(T_i-T_{i-1}\right)}+\frac{\partial\tilde{\mathcal{H}}_i}{\partial\left(T_i-T_{i-1}\right)}\right]$$

and with equations (14b) and (14c) leads to (15).

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