Optimal Taxation in the Automated Era

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Abstract

Using the consumption equivalent welfare gain as social welfare and assuming an automation technology shock, we derive the optimal tax rates for various tax policy instruments in the steady state of the model economy calibrated for the U.S. We find that the optimal capital income tax rate lies between 22 percent and 23 percent under realistic technology shocks, while the tax rate could be higher if the elasticity of substitution between automation-related capital and unskilled workers becomes greater. Another finding is that the optimal labor income tax rate for unskilled workers is lower than that for skilled workers, although the social welfare gain from such optimal labor income tax reform is very small. We also find that the optimal tax rate on automation-related capital is zero due to its large economic distortion in the long run. Furthermore, the redistributive mechanism of the optimal consumption tax depends on the elasticity of substitution between automation-related capital and unskilled workers. Finally, we find that Pareto-efficient optimal tax reform is a combination of raising the capital income tax rate and lowering the consumption tax rate from the status quo. When automation-augmented technological progress is rapid, it is even optimal to rely solely on the capital income tax rate hike as a redistributive tax policy tool.

Keywords: Automation, Optimal Taxation, Capital Income Tax, Labor Income Tax, Consumption Tax, Robot Tax, Tax Mix

JEL Classification Codes: H21, H24, H25, H30, E25, O30, O40, C68

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Introduction

How does automation affect the redistributive mechanism of fiscal policy? We study the optimal fiscal policy to address inequality caused by automation, as automation brings welfare benefits to capitalists and skilled workers but welfare loss to unskilled workers (Nakatani et al. 2022). In our paper, we define “automation” as a technology that includes the categories of “robot” and “artificial intelligence (AI)”, which may excessively automate work and fuel inequality (Acemoglu 2023). As automation technology advances rapidly in the economy, new types of capital—e.g., robotics and forms of intangible capital that include software for AI—accumulate in the economy to improve productivity (Nakatani 2024), in addition to traditional capital. In this environment, optimally sharing gains from automation depends on redistributive fiscal policy working primarily through taxation policy that maximizes social welfare. For example, Ernst et al. (2019) argue that a possible way to address both rising income inequalities and skill-biased technological change in the age of AI consists of introducing differential taxation to favor labor over capital. We contribute to the literature on optimal taxation, which historically has three streams: optimal labor income taxation, optimal capital income taxation, and the optimal combination of multiple tax instruments, as illustrated below.

Redistribution of workers’ income can be primarily achieved through labor income taxation. From this perspective, optimal labor income taxation theory was established by Mirrlees (1971), who found a linear structure to the optimal marginal income tax schedule with a zero marginal tax rate for the top-income earner. Stern (1976) studied optimal linear income taxation and found that the maximum marginal tax rate on income depends on the distribution of income and the government’s preference. Stiglitz (1982) found the optimal negative marginal tax rate on high-ability individuals, which depends on different individuals not being perfect substitutes for one another in production. Tuomala (1984) calculated the optimal nonlinear income tax rates and showed that the marginal tax rate could be regressive. In contrast, Diamond (1998) found a U-shaped optimal income tax structure. Dahan and Strawczynski (2000) demonstrated that Diamond’s U-shaped pattern depends on the linear utility of consumption. These results from the literature imply an economic intuition that equity (efficiency) consideration drives an upward-sloping (downward-sloping) marginal tax schedule. Our question is what the optimal labor income tax rate becomes in the presence of automation in the economy. Intuitively, since low-skilled workers suffer from automation, the optimal nonlinear labor income tax schedule is likely to be progressive in the automated age. However, we need to assess the desirability of labor income tax reform in comparison to the social welfare gain from changing other types of taxes in the age of automation. In relation to automation, Tyers and Zhou (2023) show that a generalization of the US ‘earned income tax credit’ system with consumption tax outperforms alternatives of the ‘universal basic income’.

Since automation benefits mainly firms and their owners (i.e., capitalists), taxing capital income seems to be the key to addressing attendant income inequality. In this regard, however, in the field of optimal capital income taxation, Chamley (1986) and Judd (1985) found that the optimal capital income tax rate is zero in the steady state because capital income taxation is harmful to capital accumulation. Judd (2002) found that the optimal capital tax may be negative under imperfect competition because the exploding distortions caused by markups in the capital market need to be reduced with subsidies. Straub and Werning (2020) recently overturned the conclusion of Chamley-Judd’s zero capital income taxation in the long run, proving that the long-run tax on capital is positive and significant when the intertemporal elasticity of substitution of capitalists is less than one. In the automated economy, capitalists gain too much from technological progress, so the zero tax rate on capital income might not be optimal, depending on societal preference, the intertemporal elasticity of substitution, and imperfect competition. Alternatively, the deadweight loss caused by capital income taxation could be magnified in the automated economy, as redistributing the gains from robot-augmented technological progress might be preferable to imposing detrimental taxes on capital accumulation that deter technological revolution. Our research is the first study to examine optimal capital income taxation in the context of automation.

The last stream of the optimal tax theory literature regards choosing a combination of various tax rates because policymakers require multiple tax policy instruments to achieve multiple policy objectives due to various tradeoffs caused by taxation, as we will see in this paper. In this respect, Atkinson and Stiglitz (1976) developed a famous theorem regarding uniform commodity taxes under nonlinear income taxation. However, this Atkinson-Stiglitz theorem was overturned by Naito (1999), who used Stolper and Samuelson's (1941) theorem to show that a nonuniform commodity tax can Pareto-improve welfare even under nonlinear income taxation if the production side of the economy is considered. Thus, we use the general equilibrium model taking into account the production side, but we stick to the uniform commodity tax rate since we only consider a single product. Rather, from the viewpoint of the optimal tax policy mix in an era of automation, we analyze the optimal combination of the capital income tax rate and consumption tax rate since this practical tax policy mix has not been previously explored in the automation literature, and we find strong results for these two tax policies, as we will show later in this paper.

A new body of literature on optimal taxation for automation, i.e., robots and AI, has recently grown (Merola 2022). Zhang (2019) found that taxing robots can improve wage inequality between skilled and unskilled workers in the face of automation. Costinot and Werning (2023) found that the optimal robot tax decreases as the process of automation deepens. Guerreiro et al. (2022) studied the combination of robot tax and the Mirrleesean labor tax and found that taxing robots is optimal only when routine workers are active in the labor force. Thuemmel (2023) found that a robot tax or subsidy is optimal depending on its price, while most welfare gains can be achieved by adjusting the income tax. However, all such literature only studies the optimal tax mix for labor and robots. Jaimovich et al. (2021) studied job retraining programs, universal basic income, transfers, and nonlinear income tax reform as potential policy options to address inequality caused by automation. However, they did not study other types of taxes or their various combinations as an optimal tax system. Therefore, in this paper, we study comprehensive fiscal policy packages that include various types of taxes in the automated economy.

Our main contribution of this paper is to calculate optimal tax rates and optimal tax mix for the U.S. economy in the steady states. In doing so, we use the dynamic general equilibrium (DGE) model by Nakatani et al. (2022), who added fiscal policy instruments, the endogenous labor supply, and nominal friction caused by monopolistic competition into the automation model originally developed by Berg et al. (2018). The analytical approach of our paper is very different from Nakatani et al. (2022) in the sense that Nakatani et al. (2022) studied the effects of fiscal policy on automated economy in the transition dynamics by allowing fiscal policy adjustment equivalent to one percent of GDP in the initial period. In contrast, we study optimality of various tax policies focusing on the steady states. Since nobody knows what the steady states in the coming future will be, we conduct a sensitivity analysis by changing key parameters. Another main difference is that we introduce the consumption equivalent welfare gain, which is often used in the macroeconomic literature (Domeij and Heathcote 2004), into Nakatani et al.'s (2022) DGE model. In the next section, we elaborate on the detailed model setting and calibration of the parameters.

Model

The economy consists of firms, workers (skilled and unskilled), owners of capital (or capitalists), and the government. The numbers of skilled workers, unskilled workers, and capitalists are denoted by N_S, N_L, and N_C, respectively. Without a loss of generality, we normalize the total population to one. Thus,$N_S + N_L + N_C = 1$.

We assume that N_C is constant over time. The ratio of skilled workers to total workers is denoted by ϕ_t, and it is dependent on public spending on education G_t, i.e., $\phi_t = \Phi(G_t)$. In reality, this value is related to government job training programs that convert unskilled workers into skilled workers.

There are three types of firms: intermediate goods firms, final goods firms, and wholesale firms. The production of intermediate goods requires the combination of traditional capital K_d, automation-related capital (which comprises robots and the intangible capital related to AI) Z_d, skilled labor S_d, and unskilled labor L_d.

The final goods are produced by combining a continuum of differentiated goods indexed by j, according to the Dixit-Stiglitz (1977) aggregator:

$$Y = \left[\int_0^1 y_{j,t}^{\frac{\epsilon-1}{\epsilon}}\, dj\right]^{\frac{\epsilon}{\epsilon-1}}, \tag{1}$$

where y_j is the quantity of output sold by wholesale firm j and ϵ is the elasticity of substitution across the differentiated goods, satisfying $1 < \epsilon < \infty$. The final goods producer maximizes profits as subject to the above production technology, taking the input price $p_{j,t}$ and the final goods price P_t as given. The profit maximization problem yields the following demand function:

$$y_{j,t} = \left(p_{j,t}/P_t\right)^{-\epsilon} Y_t, \tag{2}$$

and the aggregate price index $P_t = \left[\int_0^1 p_{j,t}^{1-\epsilon}\, dj\right]^{\frac{1}{1-\epsilon}}$. Without a loss of generality, we normalize the output price to one, i.e., $P_t = 1$.

There is a unit measure for wholesale firms. Wholesalers buy homogeneous goods from intermediate goods firms and transform them into heterogeneous goods, which are then sold to final goods firms. Their production technology is linear: $y_{j,t} = Q_{j,t}$. We assume that wholesalers are owned by capitalists and have monopolistic power to set the price of the goods they sell. This assumption reflects the fact that large tech companies enjoy monopolistic rent in the age of automation/AI/big data. Given this, the representative wholesaler chooses $Q_{j,t}$ and $p_{j,t}$ to solve the following problem:

$$\max \Pi_{j,t} = \int_0^1 \left(p_{j,t} y_{j,t} - \theta_t Q_{j,t}\right) dj, \tag{3}$$

which is subject to the demand function (1). θ_t is the price of intermediate goods. Then, we have

$$p_{j,t} = \left(\frac{\epsilon}{\epsilon-1}\right)\theta_t, \tag{4}$$

and by normalizing the price of final goods to unity, the above equation gives

$$\theta_t = (\epsilon - 1)/\epsilon. \tag{5}$$

Note that the markup can be expressed as $markup_t = 1/\theta_t$.

We assume that the markup is constant. We introduce markup because large firms (e.g., big tech companies) can take advantage of owning the platform and other digitalization-related networks, which makes their marginal costs lower than the average costs (Nakatani 2022a, 2023). This is because the costs of constructing such a network can be an entry barrier for other companies, which leads to both large market shares and markups.

The intermediate goods firm produces output by using capital K_d, robots Z_d, skilled labor S_d, and unskilled labor L_d, according to the following triple-nested CES production function:

$$Q_t = \mathrm{A}\left[a^{\frac{1}{\sigma_1}} H_t^{\frac{\sigma_1 - 1}{\sigma_1}} + (1-a)^{\frac{1}{\sigma_1}} V_t^{\frac{\sigma_1 - 1}{\sigma_1}}\right]^{\frac{\sigma_1}{\sigma_1 - 1}}, \tag{6}$$

where $A = A_0(G_t)^{\xi}$ is an aggregate productivity that is dependent on public spending on education G_t, and

$$V_t = \left[e^{\frac{1}{\sigma_2}} L_{d,t}^{\frac{\sigma_2 - 1}{\sigma_2}} + (1-e)^{\frac{1}{\sigma_2}} (b_t Z_{d,t})^{\frac{\sigma_2 - 1}{\sigma_2}}\right]^{\frac{\sigma_2}{\sigma_2 - 1}}, \tag{7}$$

$$H_t = \left[f^{\frac{1}{\sigma_3}} S_{d,t}^{\frac{\sigma_3 - 1}{\sigma_3}} + (1-f)^{\frac{1}{\sigma_3}} K_{d,t}^{\frac{\sigma_3 - 1}{\sigma_3}}\right]^{\frac{\sigma_3}{\sigma_3 - 1}}, \tag{8}$$

where σ_1 is the elasticity of substitution between composite inputs H and V, σ_2 is the elasticity of substitution between robots and unskilled workers, and σ_3 is the elasticity of substitution between capital and skilled labor. Depending on the values of these elasticities, this production technology allows for high substitution between unskilled labor and robots and complementarity between skilled labor and capital (Krusell et al. 2000) as well as between skilled labor and robots. Automation technologies displace certain worker groups from jobs for which they have a comparative advantage (Acemoglu and Restrepo 2022). In our model, we assume that unskilled workers are displaced by automation.[1]

The intermediate goods firm maximizes its profit by choosing capital, robots, and two types of labor, subject to equations (6)-(8) according to

$$\max_{K_d, Z_d, S_d, L_d} \theta_t Q_t - r_{K,t} K_{d,t} - r_{Z,t} Z_{d,t} - w_{S,t} S_{d,t} - w_{L,t} L_{d,t},$$

where r_K and r_Z are the rental rates of capital and robots, respectively, and w_S and w_L are the wage rates for skilled and unskilled workers, respectively. Then, the first-order conditions of this problem are

$$\theta_t \frac{\partial Q_t}{\partial K_{d,t}} = r_{K,t}, \qquad \theta_t \frac{\partial Q_t}{\partial Z_{d,t}} + Q_t \frac{\partial \theta_t}{\partial Z_{d,t}} = r_{Z,t}, \tag{9}$$

[1] Readers can understand automation technology in our model as industrial robots in manufacturing, for example.

$$\theta_t \frac{\partial Q_t}{\partial S_{d,t}} + Q_t \frac{\partial \theta_t}{\partial S_{d,t}} = w_{S,t}, \qquad \theta_t \frac{\partial Q_t}{\partial L_{d,t}} + Q_t \frac{\partial \theta_t}{\partial L_{d,t}} = w_{L,t} \tag{10}$$

Workers consume all of their income. The representative skilled worker's utility function is calculated by preferences as proposed by Greenwood et al. (1988) to abstract from income effects:

$$U(C_S, S) = \frac{1}{1-\sigma_S}\left(C_{S,t} - \Phi_S \frac{S_t^{1+\mu_S}}{1+\mu_S}\right)^{1-\sigma_S}, \tag{11}$$

where C_S is the consumption of skilled workers and S is the labor supply.[2] $\Phi_S > 0$ is a measure of the disutility parameter of working, and μ_S is the inverse of the Frisch elasticity. Since we know from Diamond (1998) that the optimal marginal tax rate at the bottom of the skill distribution becomes higher when there are no income effects on the utility function, we prefer this specification of the utility function to examine whether the progressive labor income tax rate is still optimal in this robust setting. The budget constraint of the skilled worker is

$$(1 + \tau_c)C_{S,t} = \left(1 - \tau_{w_S}\right)w_{S,t}S_t + \kappa, \tag{12}$$

where τ_c is the consumption tax rate, τ_{w_S} is the tax rate on skilled workers' income, and κ is the universal lump-sum transfer. The skilled worker chooses C_S and S to maximize the utility function in (11) subject to the budget constraint in (12). The first-order conditions correspond to equation (12), and

$$\Phi_S S_t^{\mu_S} = \frac{1-\tau_{w_S}}{1+\tau_c} w_{S,t}.$$

Similarly, the unskilled worker's problem can be written as

$$\max_{C_L, L} U(C_L, L) = \frac{1}{1-\sigma_L}\left(C_{L,t} - \Phi_L \frac{L_t^{1+\mu_L}}{1+\mu_L}\right)^{1-\sigma_L}, \tag{13}$$

which is subject to

$$(1 + \tau_c)C_{L,t} = \left(1 - \tau_{w_L}\right)w_{L,t}L_t + \kappa + s_L, \tag{14}$$

where τ_{w_L} is the tax rate on unskilled workers' income and s_L is the trageted transfer to unskilled workers. The first-order conditions are modeled by equation (14) and

$$\Phi_L L_t^{\mu_L} = \frac{1-\tau_{w_L}}{1+\tau_c} w_{L,t}.$$

Capitalists own firms, do not work, and save money to smooth consumption over time. These savings are invested in automation and traditional capital. This setup helps to characterize the "winner-take-all" aspect of automation as well as the fact that "the rise of the top one percent is likely very tied up with technology." The representative capitalist chooses consumption c_t, investment in capital I_K, and investment in robots I_Z to maximize

[2] We do not study the friction in the labor matching market. See Guimarães and Gil (2022) for such topic in the context of automation.

$$\max_{C,I_K,I_Z} \sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\sigma_C}}{1-\sigma_C}, \tag{15}$$

subject to the following budget constraint and the capital and robot accumulation equations:

$$(1+\tau_c)C_t + I_{K,t} + I_{Z,t} = (1-\tau)\left[r_{K,t}K_t + r_{Z,t}Z_t\right] + (1-\tau_\theta)(1-\theta)\frac{Q_t}{N_C} + \kappa - \tau_Z Z_t, \tag{16}$$

$$K_{t+1} = (1-\delta_K)K_t + I_{K,t}, \tag{17}$$

and

$$Z_{t+1} = (1-\delta_Z)Z_t + I_{Z,t}, \tag{18}$$

where β is the discount factor, δ_K is the depreciation rate of capital, δ_Z is the depreciation rate of the robots, τ is the capital income tax rate, τ_θ is the tax rate on markup, and τ_Z is the robot tax rate. We assume $\tau_\theta = \tau$ throughout the paper, i.e., the tax on markup is collected as a part of capital income taxation.

The first-order conditions of the capitalists' maximization problem include the following Euler equations:

$$\frac{\lambda_t}{\beta\lambda_{t+1}} = (1-\tau)\frac{\partial Q_{t+1}}{\partial K_{d,t+1}} + (1-\delta_K), \quad \text{and} \quad \frac{\lambda_t}{\beta\lambda_{t+1}} = (1-\tau)\frac{\partial Q_{t+1}}{\partial Z_{d,t+1}} - \tau_Z + (1-\delta_Z),$$

which at the initial steady state correspond to

$$1 = \beta\left[(1-\tau)\frac{\partial Q}{\partial K_d} + 1 - \delta_K\right], \quad \text{and} \quad 1 = \beta\left[(1-\tau)\frac{\partial Q}{\partial Z_d} + 1 - \delta_Z - \tau_Z\right].$$

The government has multiple instruments (taxes and expenditures) with which to implement fiscal policy, subject to a balanced budget in each period. The government budget constraint is given by

$$\begin{aligned} \mathrm{G}_t + \sum_{i=L,S,C} N_i\kappa + N_L s_L \\ &= N_C\left[\tau\{r_{K,t}K_t + r_{Z,t}Z_t\} + \tau_c C_t + \tau_Z Z_t\right] + \tau_\theta(1-\theta)Q_t + N_S\left[\tau_{w_S}w_{S,t}S_t + \tau_c C_{S,t}\right] \\ &\quad + N_L\left[\tau_{w_L}w_{L,t}L_t + \tau_c C_{L,t}\right]. \end{aligned}$$

We impose a nonnegative constraint for targeted transfers to unskilled workers[3]:

$$s_L \geq 0.$$

The goods market is in equilibrium when the supply of firms equals the demand of capitalists, workers, and the government:

$$Q_t = N_c\left(C_t + I_{K,t} + I_{Z,t}\right) + N_s C_{S,t} + N_L C_{L,t} + G_t.$$

The labor markets are in equilibrium when the labor demand is equal to the labor services supplied by workers:

[3] See Nakatani (2022b) for the case without such a nonnegativity constraint.

$$S_{d,t} = N_S S_t,$$

and

$$L_{d,t} = N_L L_t.$$

Similarly, the capital and robot markets are in equilibrium when

$$K_{d,t} = N_C K_t,$$

and

$$Z_{d,t} = N_C Z_t.$$

The welfare gain for skilled workers Δ_S, as defined by Domeij and Heathcote (2004), satisfies the following equation:

$$U\left(C_{S,t}^{R}, S_t^R\right) = U\left((1+\Delta_S)C_{S,t}^{NR}, S_t^{NR}\right)$$

where equilibrium consumption is represented by C_S^R in the case of tax reform and C_S^{NR} in the case of no tax reform. The same applies to superscripts of labor supply. The above equation can be rewritten as follows:

$$\frac{1}{1-\sigma_S}\left\{C_{S,t}^R - \Phi_S \frac{(S_t^R)^{1+\mu_S}}{1+\mu_S}\right\}^{1-\sigma_S} = \frac{1}{1-\sigma_S}\left\{(1+\Delta_S)C_{S,t}^{NR} - \Phi_S \frac{(S_t^{NR})^{1+\mu_S}}{1+\mu_S}\right\}^{1-\sigma_S}$$

$$\therefore \Delta_S = \left[C_{S,t}^R - \Phi_S\left\{\frac{\left(S_t^R\right)^{1+\mu_S}}{1+\mu_S} - \frac{\left(S_t^{NR}\right)^{1+\mu_S}}{1+\mu_S}\right\}\right] \Big/ C_{S,t}^{NR} - 1.$$

The same calculation yields a welfare gain for unskilled workers Δ_L:

$$\Delta_L = \left[C_{L,t}^R - \Phi_L\left\{\frac{\left(L_t^R\right)^{1+\mu_L}}{1+\mu_L} - \frac{\left(L_t^{NR}\right)^{1+\mu_L}}{1+\mu_L}\right\}\right] \Big/ C_{L,t}^{NR} - 1.$$

The welfare gain for capitalists Δ_C satisfies the following equation:

$$\sum_{t=0}^{\infty} \beta^t \frac{(C_t^R)^{1-\sigma_C}}{1-\sigma_C} = \sum_{t=0}^{\infty} \beta^t \frac{\left((1+\Delta_C)C_t^{NR}\right)^{1-\sigma_C}}{1-\sigma_C}$$

$$\therefore \Delta_C = \left\{\frac{\left(C_0^R\right)^{1-\sigma_C} + \beta\left(C_1^R\right)^{1-\sigma_C} + \beta^2\left(C_2^R\right)^{1-\sigma_C} + \cdots}{\left(C_0^{NR}\right)^{1-\sigma_C} + \beta\left(C_1^{NR}\right)^{1-\sigma_C} + \beta^2\left(C_2^{NR}\right)^{1-\sigma_C} + \cdots}\right\}^{\frac{1}{1-\sigma_C}} - 1.$$

Social welfare based on population shares, as introduced by Acemoglu and Autor (2011), is defined as follows:

$$\Delta = N_S\Delta_S + N_L\Delta_L + N_C\Delta_C.$$

A utilitarian government uses equal weights for aggregating individual welfare gains:

$$\Delta_{Utilitarian} = (\Delta_S + \Delta_L + \Delta_C)/3.$$

Calibration

The model is calibrated to match the U.S. economy. Table 1 summarizes the parameter values in the initial steady state. Following Berg et al. (2018), we set the steady-state discount rate to 0.5 percent (i.e., discount factor $\beta = 0.995$). The depreciation rates are the same for both capital and robots ($\delta_K = \delta_Z = 0.05$).

The shares in production of the composite input H, unskilled labor, and skilled labor are calibrated to match a capital income share of 0.35, an unskilled income share of 0.31, a skilled income share of 0.30, and a robot income share of 0.04. This yields a = 0.800, e = 0.988, and f = 0.058. Following Berg et al. (2018), we set the elasticity of substitution between H and V to 0.67 and the elasticity of substitution between skilled labor and capital to 0.335. We set the elasticity of substitution between unskilled labor and robots to 1.9, as estimated by DeCanio (2016). The markup is 1.19 according to Barkai (2020).

For the inverse of the Frisch elasticity, we set $\mu_L = 2$ and $\mu_S = 2$, which are taken from the intensive margin as per Chetty et al. (2011). This means that the Frisch elasticity of both unskilled and skilled labor is 0.5, which is the median value suggested in the literature. Following Berg et al. (2018), we set the intertemporal elasticity of substitution to 0.5 (i.e., $\sigma = 2$), which is the same as the mean estimated by Havranek et al. (2015). The disutility parameter of working for unskilled workers is set by targeting the steady-state working hours to be one-third (i.e., eight hours per day). The observed wage dispersion between skilled and unskilled workers—i.e., $w_S/w_L = 2$—is used to specify that the parameter of skilled workers' disutility from working as a steady-state skill premium depends on the difference in the advantage of skilled workers over unskilled workers (Afonso 2023).

The population is normalized to 1, and the share of capitalists is one percent. The share of skilled workers to total workers depends on public spending on education $\phi_t = \phi_0 G_t^{\gamma}$. Peralta and Roitman (2018) report that a four-percentage point shift from unskilled to medium/high-skilled workers costs 1-3 percent of GDP, based on education costs in the U.S. On this basis, we set $\gamma = 0.22$. We calibrate ϕ_0 to match the 55 percent share of unskilled workers, as reported by Acemoglu and Autor (2011). Education spending also affects total factor productivity (TFP). Thus, we assume that $A_t = A_0 (G_t)^{\xi}$, where ξ is the elasticity of TFP to education spending. As there are no direct empirical counterparts of ξ, we postulate that a one percentage point increase in education spending raises TFP by one percent. A_0 is set to normalize the output to one.

We calibrate the tax rates based on the latest 2014 U.S. data from the national accounts. The income (capital income as well as labor income for skilled/unskilled workers) tax rate is calibrated to match 13.17 percent of GDP, which is the actual ratio of the (individual and corporate) income tax revenue as a percentage of GDP. The consumption tax rate is calibrated to match the actual ratio of 4.48 percent, which represents the indirect tax revenue (taxes on goods and services and on international trade) as a share of GDP. As a result, we obtain 13.2 percent of the (capital and labor) income tax rate and 6.9 percent of the consumption tax rate. Note that the calibrated income tax rate is the same as the targeted ratio because the tax base corresponds to the income side of GDP, while the calibrated consumption tax rate is different from the above ratio since the tax base is different (consumption vs. GDP). Public spending on education is set to 0.041, which is consistent with U.S. data.

Results

We restrict our attention to steady states and include 50 percent of the shock to the productivity of automation-related capital in our baseline simulation. We are tackling a long-run issue, and we are not even sure what the actual timeline of the robot shock is, so the value added of computing the transition path is negligible. Any changes in tax rates are offset by the targeted redistributive transfers to unskilled workers in the balanced budget. Therefore, the lower limit of the tax rate is constrained by the nonnegativity of transfers to unskilled workers. We use two social welfare measures because the optimal fiscal policy is dependent on societal preferences (Gueorguiev and Nakatani 2021). We define the "optimal" fiscal policy at the point where the combination of tax rate(s) and nonnegative redistributive transfers to unskilled workers maximizes social welfare. The simulation results are shown in Tables 2-6. In Tables 2-5, we analyze the optimal tax reforms by changing only one tax rate at a time while keeping the other tax rates at the status-quo levels, while Table 6 shows the Pareto-efficient optimal tax reforms with a combination of two tax rates. The simulation results for each tax policy are discussed below.

A capital income tax hike improves the welfare of unskilled workers by transferring what is mainly the capitalists' gains from automation to unskilled workers (Table 2). High capital income tax rates reduce the welfare of both capitalists and skilled workers by reducing the accumulation of capital that complements skilled labor. Social welfare in Figure 1 is maximized by a 1.02 percent increase in consumption equivalent according to Acemoglu and Autor's (2011) social weights in the last column of Table 2, indicating that the optimal capital income tax rate is 22.9 percent. This is the only optimal tax reform that increases unskilled workers' welfare relative to the status quo by changing a single tax rate. In contrast, a utilitarian government prefers the lower optimal capital income tax rate of 10.9 percent, as the welfare gain for capitalists is very large.[4] This 10.9 percent of the optimal capital income tax rate for a utilitarian government hits the nonnegativity constraint of targeted transfers to unskilled workers, as we assume that the balanced budget and the targeted transfer are adjusted in response to changes in the tax rate.

The robot tax deters the accumulation of automation-related capital and limits gains from automation. This lowers the welfare of capitalists while bringing redistributive benefits from automation to unskilled workers through transfers (Table 3). We find that the welfare gain is positive for unskilled workers at very low robot tax rates between 1 percent and 3 percent. Since the tax on automation-related capital is very costly in the steady state, it is optimal not to impose such a tax, irrespective of the type of government, as shown in Figure 2. Our finding is consistent with Gasteiger and Prettner (2022), who found that the robot tax cannot induce a takeoff toward positive long-run growth. Prettner and Strulik (2020) also found that even the net income of high-skilled workers declines with the robot tax because the wage-depressing impact of reduced demand for machines and the complement of skilled workers apparently overcompensates the gains from redistribution.

A reduction in the tax rate on unskilled workers' wage income improves social welfare through an interesting channel (Table 4). Unskilled workers actually lose welfare because the lower price of unskilled labor

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[4] Atesagaoglu and Yazici (2021) also found that it is optimal not to tax capital income if the declining labor share is accompanied by a rising capital share, although they abstract from redistributive concerns.

increases labor demand by firms, which in turn reduces the utility of unskilled workers. This disutility effect from increased labor more than offsets the positive utility gained from the increased consumption of unskilled workers. The opposite holds for skilled workers. Capitalists also benefit from cheap unskilled labor when the unskilled wage income tax rate is lower than that of the status quo. As a result, the optimal tax rate is 8.6 percent in the utilitarian case and 11.1 percent in the case of Acemoglu and Autor (2011) (Figure 3). Since the 11.1 percent tax rate on unskilled workers' income is only 2.1 percentage points lower than the 13.2 percent tax rate on skilled workers' income, our simulation shows that the optimal progressivity of the wage income tax is not as high for a government that considers realistic population shares. Note that the social welfare gain based on realistic population shares determined by Acemoglu and Autor (2011) is negligible in the case of optimal unskilled labor income taxation. This is the smallest welfare gain among the other types of optimal tax rates except for the zero tax rate on robots, which is the same as the status quo (for example, it is lower than 1.02 percent of consumption in the case of optimal capital income taxation).

The optimal consumption tax rate is found to be 5.3 percent for both types of government (Table 5 and Figure 4). This is because the welfare gains for skilled workers and capitalists achieved through their increased consumption exceed the welfare loss for unskilled workers. The government can only lower the consumption tax rate by 1.6 percentage points from the status quo because it needs to balance the budget and secure nonnegative transfers to unskilled workers. The social welfare gain from this optimal consumption tax reform is the largest among the tax reforms compared in Tables 2-5, as it improves consumption for skilled workers and capitalists despite the worsened welfare of unskilled workers. Among all the optimal tax reforms in Tables 2-5, capitalists enjoy the greatest welfare gain from this optimal consumption tax rate cut.

In the final analysis, we study the combination of two tax policy instruments to find the Pareto-efficient optimal tax policy mix in an era of automation. Based on our previous results assuming a single tax policy instrument, we found that both a 22.7 percent rate of capital income tax and a 5.3 percent rate of consumption tax can achieve optimality in the context of a realistic government's preference. We first examine whether the combination of these two tax reforms can demonstrate Pareto-improving welfare, although the optimal capital income and consumption tax rates might differ from those of a single tax reform, as we combine them to avoid welfare loss for capitalists to satisfy Pareto optimality.

Table 6 shows that the Pareto-efficient capital income tax rate is between 13.3 and 15.2 percent, and the corresponding Pareto-efficient consumption tax rate is between 3.9 and 6.4 percent. Skilled workers always benefit the most from Pareto-efficient tax reform. The Pareto-efficient optimal capital income tax rate is 15.2 percent for the government with the realistic assumption of population shares and 15.1 percent for a utilitarian government. The Pareto-efficient optimal consumption tax rate is 3.9 percent for both types of government. The consumption equivalent social welfare gains from these Pareto-efficient optimal combinations of capital income and consumption taxes are higher than those from any other tax reforms studied in this paper for both types of governments. Therefore, it is fair to conclude that the Pareto-efficient optimal tax system characterized in Table 6 is the best tax reform in the age of automation.

These findings on the Pareto-efficient optimal tax mix are a reflection of the Tinbergen principle, which states that the number of policy instruments should match the number of policy objectives. For example, in the case of monetary and macroprudential policies, a combination of interest rate policy and reserve requirement policy can achieve the two objectives of economic stability and financial stability (Nakatani

2016). In our case of fiscal and redistribution policy, to achieve each of the two objectives of improving the welfare of unskilled workers and allowing the gains from automation to benefit skilled workers and capitalists, we require two tax policy instruments: capital income tax and consumption tax. This is because raising the capital income tax rate mainly reduces the welfare of capitalists; thus, the consumption tax rate needs to be lowered to offset this negative effect on capitalists' welfare. Note that as the consumption tax rate decreases, total tax revenue decreases, and thus, the amount of redistributive transfers to unskilled workers also decreases.

We performed a similar exercise to find the optimal policy mix of capital income tax and unskilled wage income tax, but there was no Pareto-efficient tax mix. The reason is as follows. When we increase the capital income tax rate, capitalists suffer from slower capital accumulation; thus, we need to lower the unskilled wage income tax rate to offset this negative welfare effect for capitalists. However, lower unskilled wage income tax revenue reduces targeted redistributive transfers to unskilled workers, which in turn worsens the welfare of unskilled workers. Our simulation results show that there is no win–win situation that improves welfare for both unskilled workers and capitalists at the same time by adjusting the capital income tax rate and unskilled wage income tax rate. As we see in Table 4, capitalists' welfare gain from unskilled wage income tax cuts is not large enough to offset the sizable negative welfare effects of capital income tax hikes.

Sensitivity Analysis

In this section, we conduct a sensitivity analysis for two critical parameters. Since the future paths of automation-related technological progress and the elasticity of substitution between automation-related capital and unskilled workers are unknown, we analyze how these two shocks affect the design of optimal tax policy. Here, we only study the optimal (i) capital income tax, (ii) unskilled wage tax, and (iii) consumption tax because we find that the imposition of a robot tax does not improve social welfare relative to the status-quo tax system. Additionally, we do not study the case for utilitarian government in this section since it underrepresents welfare for unskilled workers in society.[5] The results for the first exercise—different sizes of technology shocks—are shown in Table 7.

We find that the optimal capital income tax rate lies between approximately 22 and 23 percent, depending on the size of the automation-related productivity shock. The social welfare gain from such tax reform is approximately 1 percent of consumption. By raising the capital income tax rate, technological progress is delayed, and hence, both capitalists and skilled workers lose their welfare, but their welfare loss is more than offset by the improvement of unskilled workers' welfare due to redistribution through transfers. The consumption equivalent welfare loss is large for capitalists, although its social impact is negligible due to their very small population share. Even in the absence of a technology shock, the optimal capital income tax rate is 23.5 percent, approximately 10 percentage points higher than the status-quo rate. This finding

[5] Van Hoorn (2022) finds individuals in occupations more at risk of job loss due to automation have stronger preferences for government redistribution. This is the case for unskilled workers in our model.

corroborates the argument of Acemoglu et al. (2020), who found that the current U.S. tax system favors capital and that reducing excessive subsidies to capital would enhance welfare. Our result is also consistent with the simulation by Heer et al. (2023), who found that the decrease in the U.S. labor share under automation would have been significantly smaller if labor and capital income tax rates had remained at their respective levels of the 1960s (i.e., a higher capital income tax rate and lower labor income tax rate than the current situation). Our results show that the optimal capital income tax rate gradually decreases as the size of the automation-related productivity shock increases. This is because we have more gains from automation to redistribute toward unskilled workers, as evidenced by the increasing amount of transfers to unskilled workers if the pace of technological progress becomes faster.

We also find that the welfare gain from changing the unskilled wage income tax rate is negligible irrespective of the size of the productivity shock. This result can be attributed to the fact that monopolistic power increases the tax incidence that falls on firms, thereby making labor income taxes less effective in income redistribution than in redistribution from profits. The optimal unskilled wage tax schedule is found to be U-shaped because the targeted transfers to unskilled workers hit the nonnegativity constraint in the absence of a productivity shock. As the size of the shock increases, the changes in welfare for unskilled and skilled workers become tinier under optimal unskilled wage income taxation. In contrast, under the scenario of a 200 percent automation-related productivity shock, capitalists experience welfare loss because the optimal unskilled wage tax rate becomes higher than the status-quo rate; hence, unskilled labor becomes more expensive for firms that distribute capital gains to capitalists.

Furthermore, we find that it is optimal to lower the consumption tax rate in the automated economy because the welfare loss for unskilled workers is more than offset by the welfare gains for skilled workers and capitalists. The optimal consumption tax rate is set at the point where the transfers to unskilled workers do not become negative. This means that as long as all three economic agents receive the same amount of universal lump-sum transfers as in the status-quo economy, the welfare gains from automation could be shared between skilled workers and capitalists under the optimal consumption tax, although unskilled workers do not receive additional transfers due to the reduced consumption tax rate. Thus, the optimal consumption tax policy by itself is not an appropriate policy tool for rescuing losers in the automated economy—i.e., unskilled workers.

Similar to Table 6, we study the Pareto-efficient optimal tax mix for different sizes of technology shocks in Table 8. We find that as the size of the technology shock becomes larger, the optimal capital income tax rate increases, and the optimal consumption tax rate decreases. An economic intuition is that when automation-related technological progress is faster, capital income taxation needs to be increased to redistribute more wealth from capitalists to unskilled workers because the widening inequality gap becomes larger between them. However, to achieve Pareto efficiency, the consumption tax rate must be lowered to offset the negative effects on capitalists' welfare. As a result, skilled workers always gain their welfare the most from optimal reform of the tax mix, as they are less engaged in the tradeoff caused by capital income taxation and consumption taxation.

We find two particularly interesting results in Table 8. First, even in the absence of an automation-related technology shock, it is Pareto-efficient and optimal to increase the capital income tax rate by 0.7 percentage points (from the status-quo 13.2 percent to 13.9 percent) and lower the consumption tax rate by 1.2 percentage points (from the status-quo 6.9 percent to 5.7 percent) in the U.S. Second, in the case of a very large (i.e., 200 percent) increase in the productivity of automation-related capital, the optimal tax policy mix is to raise only the capital income tax rate without imposing a consumption tax. This is an interesting finding that no other researchers have found thus far. Thus, our new results show that policymakers should rely on a higher capital income tax rate as a redistribution policy tool, but they should not tax consumption when automation-related technological progress is very fast.

Next, we conduct another sensitivity analysis regarding the most unknown but critical parameter—the elasticity of substitution between unskilled labor and automation-related capital (σ_2).[6] Following Berg et al. (2018), we examine the values up to $\sigma_2 = 20$. To avoid changes in other parameters, we use the same values of parameters calibrated in Table 1 and change only the value of σ_2 as a shock in the new steady state. The results are shown in Table 9.

We find that the optimal capital income tax rate could exceed 30 percent if the elasticity of substitution between unskilled labor and automation-related capital is greater because more unskilled labor will be replaced by automation technology; hence, there is a need for greater redistribution via transfers to improve unskilled workers' welfare. As a result, the social welfare gain from a capital income tax hike is larger when the substation is higher.

With regard to optimal labor income taxation, if the elasticity of substitution between automation-related capital and unskilled labor becomes greater, it is noteworthy that the redistribution mechanism of optimal fiscal policy changes. Specifically, the government should impose a higher labor income tax rate for unskilled workers to increase their wages so that firms demand less labor. Then, the disutility from working decreases for unskilled workers, which improves their welfare. The additionally collected tax revenues can be redistributed to unskilled workers so that they can increase their consumption. Through both these channels of utility from working and consumption, unskilled workers' welfare increases. However, the social welfare gain from changing taxes on unskilled workers' income is still nil irrespective of the value of the elasticity of substitution between automation-related capital and unskilled labor.

Finally, we find very interesting results for the optimal consumption tax in response to a shock to the elasticity of substitution between unskilled workers and automation-related capital. When the elasticity of substitution between unskilled labor and automation-related capital is 2.5, it is optimal not to impose a consumption tax. Unskilled workers face a welfare loss, but it is more than offset by welfare gains for the other two agents. However, if the elasticity of substitution is greater than 5, the mechanism of the optimal consumption tax policy becomes the opposite. Specifically, it is optimal to collect consumption taxes from skilled workers and capitalists and then redistribute those resources to unskilled workers through transfers. Therefore, in contrast to the findings in Tables 5 and 7, the welfare for unskilled workers actually improves when the elasticity of substitution between them and automation-related capital is high.

We also searched for the optimal tax reform that Pareto-improves social welfare under the elasticity of substitution shock. However, we could not find any such reform as a combination of a changing capital

[6] We also examined the other values of the elasticity of substitution (σ_1 and σ_3) in the production function, but the results did not change significantly. The results for such exercise are available upon request.

income tax rate and consumption tax rate because the redistributive mechanism of optimal capital income and consumption tax rates works in the same direction among agents when the substitution shock becomes larger (as evidenced by Table 9).

Conclusion

We studied the optimal tax policy in the automated economy and reached the following conclusions. First, we find that there is no Pareto-efficient fiscal policy instrument if we change only a single tax rate. Second, the optimal capital income tax rate is found to be approximately 23 percent in the near term. Third, it is not optimal to impose a robot tax, as its long-run cost is large. Fourth, lowering the personal income tax rate for unskilled workers could be an optimal progressive labor income tax policy option to maximize the social welfare of society, while its social welfare gain is small. Fifth, the optimal consumption tax rate is lower than the status quo, while the redistribution mechanism changes depending on the elasticity of substitution between automation-related capital and unskilled workers. Finally, we found that Pareto-efficient optimal tax reform is a combination of raising the capital income tax rate and lowering the consumption tax rate. This optimal tax reform is welfare improving in a Pareto-efficient way in the status-quo economy even in the absence of a technology shock. This Pareto-efficient optimal capital income tax rate for the realistic level of technology shock is 2 percentage points higher, and this Pareto-efficient optimal consumption tax rate is 3 percentage points lower than that of the status-quo economy. Thus, the main policy implication is that an increase in the capital income tax rate could improve social welfare in a Pareto-efficient way if the tax reform is supplemented by lowering the consumption tax rate in an age of automation. If the speed of automation-augmented technological shock is very fast, Pareto-efficient optimal tax reform is a combination of relying solely on capital income tax rate hikes as a redistributive tax policy tool and reducing the consumption tax rate to zero to alleviate the negative welfare effects for capitalists.

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Figure 1: Social Welfare Change under Optimal Capital Income Tax Rate

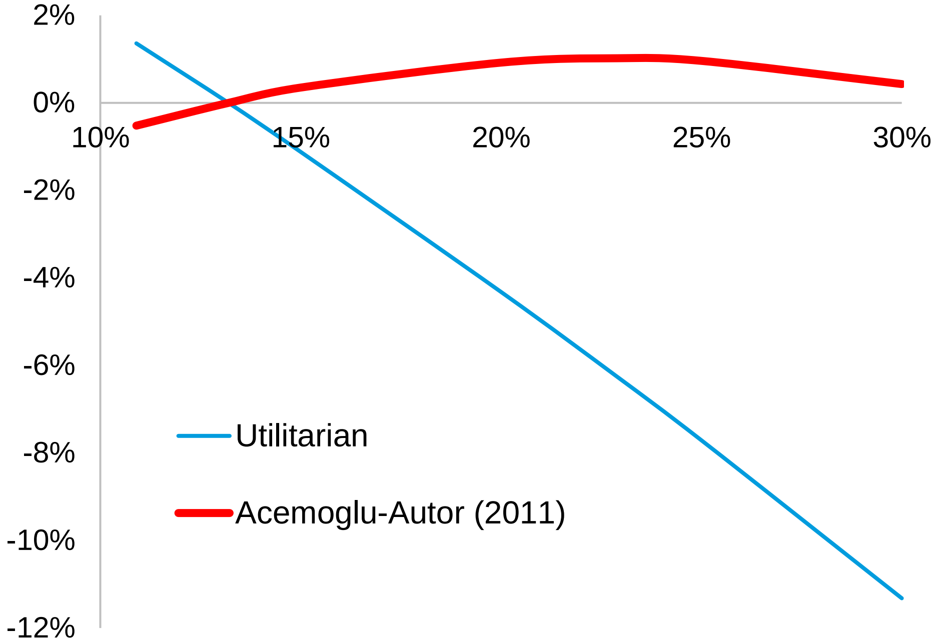

Figure 2: Social Welfare Change under Optimal Robot Tax Rate

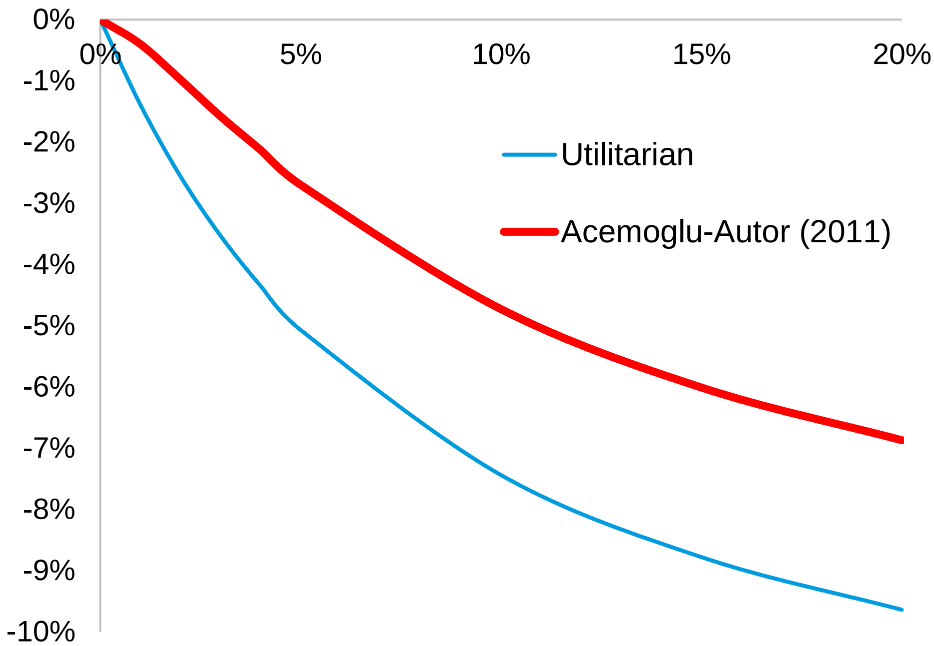

Figure 3: Social Welfare Change under Optimal Unskilled Wage Income Tax Rate

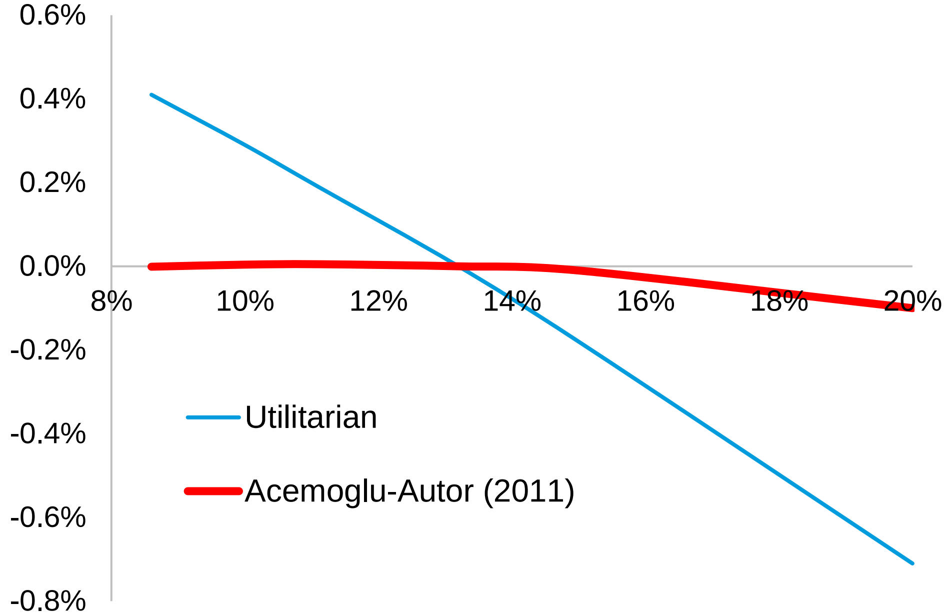

Figure 4: Social Welfare Change under Optimal Consumption Tax Rate

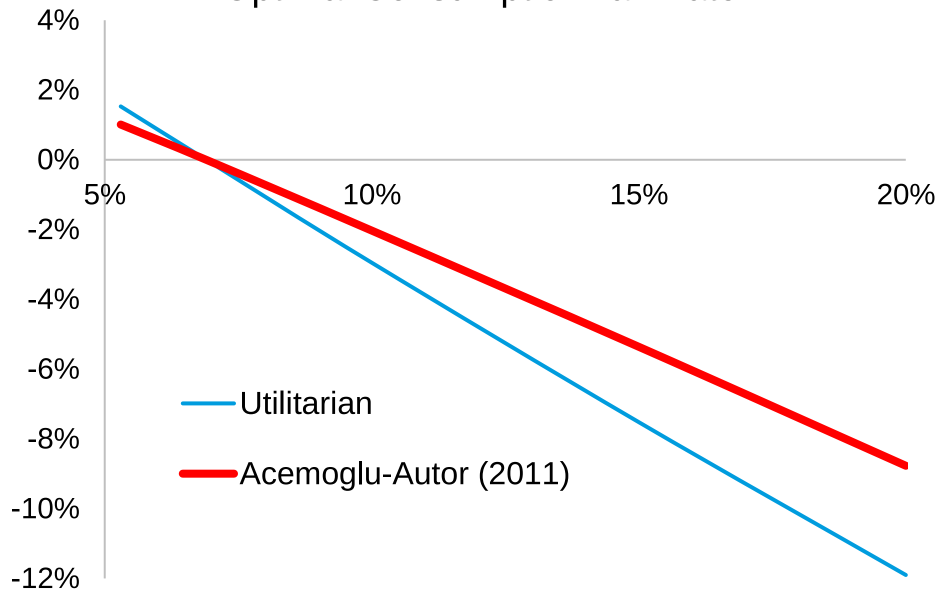

Table 1. Calibration

Parameter	Description	Value	Source or Target
b	Productivity of automation technology	0.5	Berg et al. (2018)
σ_1	Elasticity of substitution between composite capital and composite labor	0.67	Berg et al. (2018)
σ_2	Elasticity of substitution between unskilled labor and automation-related capital	1.9	DeCanio (2016)
σ_3	Elasticity of substitution between skilled labor and capital	0.335	Berg et al. (2018)
a	Share parameter of composite labor in production	0.800	Berg et al. (2018)
e	Share parameter of unskilled labor in composite labor	0.988	Berg et al. (2018)
f	Share parameter of skilled labor in composite capital	0.058	Berg et al. (2018)
σ_L	The inverse of intertemporal elasticity of substitution for unskilled workers	2	Berg et al. (2018)
σ_S	The inverse of intertemporal elasticity of substitution for skilled workers	2	Berg et al. (2018)
σ_C	The inverse of intertemporal elasticity of substitution for capitalists	2	Berg et al. (2018)
μ_L	The inverse of Frisch elasticity of unskilled labor supply	2	Chetty et al. (2011)
μ_S	The inverse of Frisch elasticity of skilled labor supply	2	Chetty et al. (2011)
Φ_L	Disutility of unskilled work	10.4	L=1/3 (i.e., 8 hours)
Φ_S	Disutility of skilled work	59.2	w_s/w_l=2
β	Discount factor	0.995	Berg et al. (2018)
δ_K	Depreciation rate of capital	0.05	Berg et al. (2018)
δ_Z	Depreciation rate of robots	0.05	Berg et al. (2018)
$\emptyset_0$	Parameter for population share function	0.909	Acemoglu and Autor (2011)
ξ	Elasticity of TFP to education spending	0.22	Peralta and Roitman (2018)
A_0	Initial total factor productivity	0.279	Berg et al. (2018)
$\tau, \tau_{w_L}, \tau_{w_S}$	Tax rate on income from skilled/unskilled labor or capital	0.132	U.S. data (13.17 percent of GDP)
τ_c	Tax rate on consumption	0.069	U.S. data (4.48 percent of GDP)
ϵ	The elasticity of substitution (implied markup is 1.19)	6.263	Barkai (2020)

Table 2. Social Welfare Change under the Optimal Capital Income Tax Rate

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
10.9%	-2.24%	1.47%	4.85%	**1.36%**	-0.52%
13.2%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
15%	1.68%	-1.19%	-3.85%	-1.12%	0.35%
20%	5.63%	-4.49%	-14.09%	-4.32%	0.92%
22.9%	7.50%	-6.44%	-19.83%	-6.26%	**1.02%**
25%	8.64%	-7.86%	-23.90%	-7.71%	0.96%
30%	10.63%	-11.29%	-33.29%	-11.32%	0.43%

Notes: A red result is the optimal capital income tax rate for Acemoglu and Autor's (2011) social weights, and a blue result is the optimal capital income tax rate for a utilitarian government. The result with the status-quo capital income tax rate is shown in bold letters.

Table 3. Social Welfare Change under the Optimal Robot Tax Rate

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
0%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
1%	0.69%	-1.67%	-3.20%	-1.39%	-0.40%
2%	0.68%	-2.90%	-5.46%	-2.56%	-0.98%
3%	0.38%	-3.84%	-7.14%	-3.53%	-1.58%
4%	0.00%	-4.60%	-8.44%	-4.35%	-2.13%
5%	-0.52%	-5.21%	-9.48%	-5.07%	-2.70%
10%	-2.64%	-7.11%	-12.56%	-7.44%	-4.73%
15%	-4.14%	-8.11%	-14.09%	-8.78%	-6.01%
20%	-5.20%	-8.72%	-15.01%	-9.64%	-6.87%

Notes: The policy experiment starts with a 1% tax rate on robots because 0% is the same as the status-quo tax regime. A red result is the optimal robot tax rate for Acemoglu and Autor's (2011) social weights, and a blue result is the optimal robot tax rate for a utilitarian government. The purple robot tax rate is optimal for both welfare criteria. The result with the status-quo robot tax rate is shown in bold letters.

Table 4. Social Welfare Change under the Optimal Unskilled Wage Income Tax Rates

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
8.6%	-0.53%	0.62%	1.15%	**0.41%**	-0.001%
10%	-0.36%	0.43%	0.80%	0.29%	0.004%
11.1%	-0.23%	0.28%	0.53%	0.19%	**0.005%**
13.2%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.000%**
15%	0.19%	-0.25%	-0.47%	-0.18%	-0.01%
20%	0.64%	-0.97%	-1.81%	-0.71%	-0.10%

Notes: A red result is the optimal unskilled wage income tax rate for Acemoglu and Autor's (2011) social weights, and a blue result is the optimal unskilled wage income tax rate for a utilitarian government. The result with the status-quo unskilled wage income tax rate is shown in bold letters.

Table 5. Social Welfare Change under the Optimal Consumption Tax Rate

Tax Rate	Individual Welfare			Social Welfare	
	Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
5.3%	-0.41%	2.72%	2.29%	**1.53%**	**1.01%**
6.9%	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
10%	0.62%	-5.21%	-4.27%	-2.95%	-2.03%
15%	1.11%	-13.15%	-10.52%	-7.52%	-5.36%
20%	1.08%	-20.65%	-16.13%	-11.90%	-8.77%

Notes: A red result is the optimal consumption tax rate for Acemoglu and Autor's (2011) social weights, and a blue result is the optimal consumption tax rate for a utilitarian government. The purple consumption tax rate is optimal for both welfare criteria. The result with the status-quo consumption tax rate is shown in bold letters.

Table 6. Social Welfare Change under the Optimal Combination of the Capital Income Tax Rate and the Consumption Tax Rate

Capital Income Tax Rate	Consumption Tax Rate	Individual Welfare			Social Welfare	
		Unskilled Workers	Skilled Workers	Capitalists	Utilitarian	Acemoglu-Autor (2011)
13.2%	**6.9%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
13.3%	6.4%	0.00%	0.74%	0.41%	0.38%	0.33%
13.4%	6.1%	0.00%	1.18%	0.63%	0.60%	0.53%
13.5%	5.7%	0.00%	1.81%	0.99%	0.93%	0.82%
13.6%	5.3%	0.00%	2.43%	1.36%	1.26%	1.10%
13.7%	5%	0.00%	2.88%	1.58%	1.49%	1.30%
13.8%	4.8%	0.00%	3.16%	1.66%	1.61%	1.42%
13.9%	4.8%	0.16%	3.09%	1.44%	1.56%	1.48%
14%	4.7%	0.22%	3.20%	1.37%	1.60%	1.56%
14.1%	4.6%	0.29%	3.30%	1.30%	1.63%	1.64%
14.2%	4.6%	0.39%	3.23%	1.08%	1.57%	1.66%
14.3%	4.5%	0.46%	3.33%	1.01%	1.60%	1.74%
14.4%	4.4%	0.53%	3.44%	0.94%	1.64%	1.83%
14.5%	4.4%	0.62%	3.37%	0.72%	1.57%	1.85%
14.6%	4.3%	0.69%	3.47%	0.65%	1.60%	1.93%
14.7%	4.2%	0.76%	3.57%	0.58%	1.64%	2.01%
14.8%	4.2%	0.85%	3.50%	0.36%	1.57%	2.03%
14.9%	4.1%	0.92%	3.60%	0.29%	1.60%	2.11%
15%	4%	0.98%	3.71%	0.22%	1.64%	2.19%
15.1%	**3.9%**	1.05%	3.81%	0.15%	**1.67%**	2.27%
15.2%	**3.9%**	1.14%	3.74%	0.00%	1.63%	**2.29%**
15.5%	3.7%	1.37%	3.87%	-0.43%	1.60%	2.47%
16%	3.3%	1.72%	4.19%	-0.94%	1.66%	2.79%

Notes: The pink-colored results are Pareto-efficient tax rates. Among these Pareto-efficient results, a red result is the Pareto-efficient optimal capital income and consumption tax rates for Acemoglu and Autor's (2011) social weights, and a blue result is the Pareto-efficient optimal capital income and consumption tax rates for a utilitarian government. The result with the status-quo capital income and consumption tax rates is shown in bold letters.

Table 7. Social Welfare Change under the Optimal Tax Rates for Different Sizes of Technology Shock

Size of Productivity Shock	***0%***	***30%***	***50%***	***100%***	***150%***	***200%***
Optimal Capital Income Tax Rate	**23.5%**	**23.1%**	**22.9%**	**22.4%**	**22.2%**	**22.0%**
Social Welfare Gain	1.04%	1.02%	1.02%	1.02%	1.05%	1.09%
Unskilled Workers' Welfare Gain	7.50%	7.48%	7.50%	7.53%	7.72%	7.90%
Skilled Workers' Welfare Gain	-6.36%	-6.40%	-6.44%	-6.47%	-6.65%	-6.77%
Capitalists' Welfare Gain	-20.38%	-19.99%	-19.83%	-19.34%	-19.36%	-19.30%
Targeted Transfers to Unskilled Workers	0.08	0.09	0.10	0.11	0.13	0.14
Optimal Unskilled Wage Tax Rate	**11.3%**	**10.7%**	**11.1%**	**12.0%**	**12.8%**	**13.7%**
Social Welfare Gain	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Unskilled Workers' Welfare Gain	-0.21%	-0.28%	-0.23%	-0.13%	0.00%	0.00%
Skilled Workers' Welfare Gain	0.27%	0.34%	0.28%	0.15%	0.00%	0.00%
Capitalists' Welfare Gain	0.50%	0.64%	0.53%	0.28%	0.00%	-0.12%
Targeted Transfers to Unskilled Workers	0.00	0.01	0.01	0.03	0.04	0.06
Optimal Consumption Tax Rate	**6.2%**	**5.6%**	**5.3%**	**4.5%**	**3.8%**	**3.1%**
Social Welfare Gain	0.46%	0.83%	1.01%	1.45%	1.78%	2.08%
Unskilled Workers' Welfare Gain	-0.13%	-0.30%	-0.41%	-0.80%	-1.27%	-1.83%
Skilled Workers' Welfare Gain	1.15%	2.19%	2.72%	4.16%	5.45%	6.77%
Capitalists' Welfare Gain	0.97%	1.84%	2.29%	3.49%	4.57%	5.67%
Targeted Transfers to Unskilled Workers	0.00	0.00	0.00	0.00	0.00	0.00

Notes: Social welfare gains are calculated with Acemoglu and Autor's (2011) social weights. Red results of targeted transfers to unskilled workers are pinned down by the nonnegativity constraint.

Table 8. Social Welfare Change under the Pareto-Efficient Optimal Combination of the Capital Income Tax Rate and the Consumption Tax Rate for Different Sizes of Technology Shock

Size of Productivity Shock	***0%***	***30%***	***50%***	***100%***	***200%***
Optimal Capital Income Tax Rate	**13.9%**	**14.7%**	**15.2%**	**16.0%**	**17.4%**
Optimal Consumption Tax Rate	**5.7%**	**4.6%**	**3.9%**	**2.5%**	**0.0%**
Social Welfare Gain	0.93%	1.77%	2.29%	3.21%	4.64%
Unskilled Workers' Welfare Gain	0.43%	0.89%	1.14%	1.38%	1.46%
Skilled Workers' Welfare Gain	1.56%	2.90%	3.74%	5.51%	8.62%
Capitalists' Welfare Gain	0.18%	0.04%	0.00%	0.08%	0.24%

Note: Social welfare gains are calculated with Acemoglu and Autor's (2011) social weights.

Table 9. Social Welfare Change under the Optimal Tax Rates for Different Elasticities of Substitution between Automation-Related Capital and Unskilled Workers

Elasticity of Substitution: σ_2	***1.9***	***2.5***	***5***	***10***	***15***	***20***
Optimal Capital Income Tax Rate	**22.9%**	**21.2%**	**28.7%**	**31.3%**	**31.9%**	**32.2%**
Social Welfare Gain	1.02%	1.67%	9.99%	11.66%	11.97%	12.10%
Unskilled Workers' Welfare Gain	7.50%	10.25%	30.89%	34.20%	34.73%	34.96%
Skilled Workers' Welfare Gain	-6.44%	-8.32%	-14.51%	-14.76%	-14.69%	-14.68%
Capitalists' Welfare Gain	-19.83%	-20.64%	-36.62%	-39.26%	-39.69%	-39.93%
Targeted Transfers to Unskilled Workers	0.10	0.24	1.50	2.31	2.56	2.69
Optimal Unskilled Wage Tax Rate	**11.1%**	**20.6%**	**26.7%**	**25.2%**	**24.6%**	**24.3%**
Social Welfare Gain	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Unskilled Workers' Welfare Gain	-0.23%	0.54%	0.00%	0.00%	0.00%	0.00%
Skilled Workers' Welfare Gain	0.28%	-0.51%	0.00%	0.00%	0.00%	0.00%
Capitalists' Welfare Gain	0.53%	-1.00%	0.00%	0.00%	0.00%	0.00%
Targeted Transfers to Unskilled Workers	0.01	0.17	0.86	1.23	1.35	1.40
Optimal Consumption Tax Rate	**5.3%**	**0.0%**	**31.5%**	**33.1%**	**33.1%**	**33.1%**
Social Welfare Gain	1.01%	1.67%	8.52%	10.15%	10.29%	10.34%
Unskilled Workers' Welfare Gain	-0.41%	-7.86%	49.34%	54.43%	54.74%	54.84%
Skilled Workers' Welfare Gain	2.72%	13.11%	-40.53%	-43.07%	-43.12%	-43.15%
Capitalists' Welfare Gain	2.29%	11.03%	-28.77%	-30.21%	-30.21%	-30.21%
Targeted Transfers to Unskilled Workers	0.00	0.00	2.25	3.47	3.83	4.00

Notes: Social welfare gains are calculated with Acemoglu and Autor's (2011) social weights. A red result of targeted transfers to unskilled workers is pinned down by the nonnegativity constraint.