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Abstract

This paper explores the consequences of automation for public finance. We find that as the automation rate increases, the government size, measured as the fiscal revenues to output ratio, declines due to the substitution of traditional inputs which bear the burden of taxes by the new automatic technology. These results are explained by the effects of automation on labor, where taxation of labor income (including social security contributions) represents the most important source of fiscal revenues in most advanced economies. The paper performs two additional counterfactual experiments. First, we calculate how individual tax rates should be changed in response to automation in order to keep constant fiscal revenues from the different sources of taxes. However, this experiment reveals that this fiscal policy would have significant harmful effects on output and labor, and that a deep reform of the current tax mix is compulsory to offset the effects of automation on public finance. Second, we calculate the tax rate on capital, without modifying the other tax rates, required to keep constant the size of the government, resulting in a capital income tax rate of around 0.77 for an automation rate of 45%.

Keywords: Automation; Taxes; Fiscal revenues; Autonomous capital; Traditional inputs.
JEL Classification: E22, E23, H30, O33.

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1. Introduction

The impressive technological progress in hardware combined with advances in Artificial Intelligence (AI) observed in the last decade has raised a number of concerns about the economic implications of the incoming fourth industrial revolution for human labor and income distribution. In some cases, these concerns resemble a revival of Luddite ideas regarding incorporation of a new type of capital to production activities as a disruptive technology. These reactionary thoughts find their explanation in the predictions made by AI experts, affirming that there is a 50% chance of AI outperforming humans in all tasks in 45 years and of automating all human jobs in 120 years (Grace *et al.*, 2017). This progressive process of AI gaining competitive advantages against humans promises to have a huge impact in labor markets as has never been seen before.[1] The main characteristic of this new technological revolution is that humans seem to have a minor space to compete with automation and this space is reduced even more as AI and robotics outperform high-skilled human workers even in cognitive and creative tasks, and not just in routine and repetitive tasks as in previous technological revolutions. Faced with this disturbing scenario, it has been common to hear about the necessity of controlling and regulating the new disruptive technology in order to protect workers and economic stability. See for example, Frey and Osborne (2017), Manyika *et al.* (2017), Aum *et al.* (2018), Berg *et al.* (2018), and Acemoglu and Restrepo (2020).

The potential impact, particularly on labor, of this combination of AI and robots is in the frontline of the current economic debate. However, the anticipated effects of "intelligent" automation does not have a clear answer. Whereas some authors adopt a Luddite view, predicting a scenario with automation displacing human labor (Acemoglu and Restrepo, 2020; Korinek and Stiglitz, 2021), other authors state that the potential impact of the current generation of robots is limited (Fernández-Macías *et al.*, 2021). In this line, other authors draw attention to positive effects of automation on productivity and economic growth (Autor, 2015; Graetz and Michaels, 2018), and to increases in aggregate employment (Klenert *et al.*, 2022), and encouraging the creation of new tasks (Acemoglu and Restrepo, 2018).[2]

[1] In particular, it is predicted that AI will outperform humans in translating languages (by 2024), writing high-school essays (by 2026), driving a truck (by 2027) and working in retail (by 2031). Furthermore, in the next decades the process would make AI outperforming humans at writing a bestselling book (by 2049) and working as a surgeon (by 2053).

[2] It is important to note that the concept of what a "robot" is varies from one paper to another, leading to different specifications of how robots are incorporated into the aggregate production function. For some

This paper explores a new dimension of automation not previously studied in the literature for the best of our knowledge: its impact on public finance. According to the aforementioned predictions, the current technological revolution also presents a challenging scenario for public finance. Automation will change the relative importance of inputs in the economy and the way in which income is distributed among production factors. These changes will have a direct impact on public finance given current the tax mix. Recently, the debate has revolved around how to tax the new autonomous capital. Although numerous authors have claimed the necessity of taxing robots, the literature lacks on analyzing the effects of robotization for public finance based on the current tax mix. This paper contributes to the literature by analyzing how public finance evolves with the expansion in the economy of the new disruptive autonomous technology. In particular, we examine how total tax revenues, including social security contributions, evolves with automation in the long-run. In order to carry out this analysis, we use the automation model by Casas and Torres (2021), extended with taxes. Using the steady-state solution of the calibrated model, we carry out three experiments to explore how tax revenues evolve as the new autonomous technology spread through the economy. First, we study how the government size, measured by the fiscal revenues to output ratio, changes as automation increases. We find that as automation increases, the competition between the traditional technology and the autonomous technology leads to a fall in the size of the government. Automation expands output in the long-run but provokes a reallocation of inputs with the subsequent impact on public finance, depending on how the tax mix is designed. Capital income tax revenues remains almost constant, but we find a dramatic reduction in labor income tax revenues and in social security contributions. This is explained by the negative response of labor to automation, where a large fraction of labor is substituted by autonomous capital. These results warn that the standard tax mix adopted by advanced economies, where labor payroll taxes represent a significant fraction of fiscal revenues, is not able to maintain the size of the government as automation increases.

Second, we calculate how tax rates should be adjusted to keep fixed the fiscal revenues. As expected, the payroll taxes rates and the consumption tax rate should be increased pro-

authors (i.e., Thuemmel, 2022), a robot is a machine that replaces low-skill workers. In this case, a robot is not different from other traditional capital equipment assets. Other authors (Lin and Weise, 2019) propose a specification for technology in which robots are substitutes of labor, without distinguish between low- and high-skill workers. In this paper we adopt the interpretation of "autonomous" or "intelligent" capital as a combination of robots and AI, and following Casas and Torres (2021), we consider that this autonomous capital is substitute for both traditional capital equipment and labor.

gressively as automation increases, to compensate the decline in the tax bases due to the reduction in working hours and the rise in the investment to output ratio to compensate the higher depreciation rate of autonomous capital, respectively. By contrast, we find that the capital tax rate could be reduced slightly as capital income increases because of the accumulation of autonomous capital. However, this type of tax policy would have dramatic harmful effects on economic activity, reducing output and consumption and further depressing labor supply. The results from this experiment arise an important question about how the tax mix scheme should be reformed to accommodate the effects of automation. To answer the above question, the third experiment consists in the calculation of the capital income tax rate necessary to keep fixed total fiscal revenues, without changes in the other tax rates. We find that the capital income tax rate should increase as the rate of automation increases, reaching a value of around 77%, for an automation rate of 45%.

Finally, we carry out a sensitivity analysis to assess the robustness of previous results to different calibrations of the key parameters of the model and alternative specifications of the technology. First, we study how the results from the previous experiments change to alternative values of the elasticity of substitution between the traditional and the new technology. Second, we repeat the simulations using an alternative aggregate production function widely used in the literature, where the autonomous technology is substitute of labor. In both cases, we find that results and insights are robust to alternative calibration and to the alternative specification of the technology.

The structure of the rest of the paper is as follows. Section 2 discusses the related literature. Section 3 presents a stylized model for automation, where two types of technologies are considered: traditional technology using traditional capital and labor, and autonomous technology using an autonomous capital resulted from the combination of robots and AI. The model considers a full specified tax menu, including a consumption tax, a labor tax, a capital income tax and a social security tax which payment splits between employees and employers. Section 4 presents the calibration of the model. Section 5 presents the main results from the three experiments. Section 6 presents the sensitivity analyses. Finally, Section 7 collects the main conclusions.

2. Related literature

Our paper is related to the literature on taxing robots. The idea of taxing robots is not new and a tax on labor-saving machinery as a policy to help displaced workers already appeared in the US throughout the Great Depression of the 1930s (Woirol, 2018). Several proposals have been done to taxing robots with two objectives: first, delay or discourage automation, and second, to obtain additional public revenues to be transferred to displaced workers and to sustain the social security system. In this venue, the potential negative effects of automation on human labor has also raised concerns about pay-as-you-go social security system sustainability (Jimeno, 2019; and Basso and Jimeno, 2019) and voices demanding for an universal basic income (Hoynes and Rothstein, 2019; Cabrales *et al.,* 2020; Jaimovich *et al.*, 2021).

Guerreiro *et al.*, (2022) defend that it is optimal to tax robots while there is still routine workers, but once all these workers are retired (automatized), the optimal robot tax should be zero. Vermuelen *et al.*, (2020) propose the distinction across economies with labor surplus and labor scarcity, arguing that only in case of labor surplus it is commendable to tax robots to prevent robotization in order to avoid exacerbate unemployment and wage stagnation. These studies could be linked to the one developed by Thuemmel (2022), who interpret robots as substitute for routine labor and complement for non-routine labor to affirm that the optimal robot tax is positive and generates small welfare gains. However, as the price of robots falls, inequality rises and the specific robot tax and its welfare impact become insignificant. When robots get cheap enough to replace all routine labor, the robot tax turns meaningless. Zhang (2019) remarks the importance of a tax on robots as an useful tool to narrow down the wage gap between unskilled and skilled workers. Moreover, Gasteiger and Prettner (2022) show that a robot tax has the potential to raise per capita output and welfare.

However, specific robots taxes arises a number of difficulties. Mazur (2019) cautions against the use of a robot tax arguing that it is the wrong tool to face the issues driven by automation and warns of the potential consequences of such tax, remarking the limiting of innovation. Moreover, Marwala (2018) put the focus on the difficulty of distinguishing what a robot is and what a robot is not and concludes that taxing robots is the same as increasing corporate taxes. This difficult task of defining what a robot is and tax it, have lead to several approaches and legal analysis about this matter. Chekina *et al.*, (2018) propose applying taxation to new cyber-physical technologies and products of their application, replacing digital transactions and shortfalls in revenues by traditional objects of taxation in the form of tangible assets and people, increasing tax pressure and the degree of progressiveness of taxes and building a new tax space with smart taxes based on real-time principles, smart contracts and Big Data. Costinot and Werning (2018) analyze technology regulation in a second best world, with rich heterogeneity across households, linear taxes on the subset of firms affected by technological change, and a nonlinear tax on labor income.

With a broader focus, Kovacev (2020) analyze diverse tax systems to conclude that any tax system that relies on human effort to raise revenues is vulnerable to dislocation with the rise of AI and robotics, while Oberson (2019) remarks that tax issues go much beyond the borders of any particular state and argues that they should be analyzed globally taking into account the recent developments in international taxation.[3]

This paper is also related to the literature exploring the macroeconomics implications of government size. Galí (1994) parameterizes the government size by the income tax rate and the share of government purchases in output, but the focus is studying the effects of government size on output variability. Standard RBC model implies that income tax are destabilizing whereas government purchased are stabilizing. Fatás and Mihov (2001) find a negative correlation between government size and output volatility both for the OECD countries and across US states. Guo and Harrison (2006) show that the stabilization effects of government fiscal policy is affected by how hours worked are introduced in the households' utility function. They found that the results of previous literature are reversed when preferences are instead convex in hours worked. Here, we adopt a different perspective by accounting how automation impacts on the government size from the tax revenues perspective.

3. The model

We consider a model economy with two types of capital: traditional capital and autonomous capital (a combination of AI and robotics). We propose a simple production function where two different technologies can coexist simultaneously: a traditional technology that requires traditional physical capital and labor for production and a new autonomous technology that employs only a new capital (hardware and artificial intelligence) for production. Whereas traditional technology uses a combination of traditional capital and labor under constant returns to scale (which implies that marginal productivity for both inputs

[3]In general, the debate about the robot tax could be understood as a sub-branch of the economic debate about the optimal capital taxation. Recently, Straub and Werning (2020) revisited the Chamley-Judd result (capital should not be taxed in the long run) to overturn it. On the one hand, they affirm that the long run tax on capital is positive and significant for the main model in Judd (1985) if the intertemporal elasticity of substitution is below one, while it converges to zero at a slow rate (maybe after centuries of high tax rates) for higher elasticities. On the other hand, they provide conditions under which the upper bound on capital taxes in Chamley (1986) binds forever implying positive long-run taxes.

is decreasing), the new technology exhibits constant marginal productivity for autonomous capital, which involves endogenous growth. We consider a representative household that can freely decide labor time, consumption and investment decisions in both kinds of capital. The model includes a government that collect taxes to finance public spending. Five tax rates are considered: a consumption tax, a capital income tax, a labor income tax, and contributions to social security by employers and employees. The model is specified in discrete time and it is considered a decentralized economy where households maximize utility in a deterministic intertemporal optimization setting and firms operates in a perfect competition environment.

3.1. The technology

The aggregate production technology is a CES function for traditional technology using capital and labor nested into another CES function. In this aggregate CES function, new and traditional technology are substitutes. We define the following aggregate production function to represent these technological combinations:

$$Y_t = \left[\mu X_t^{\upsilon} + (1-\mu)\, {D_t}^{\upsilon}\right]^{\frac{1}{\upsilon}} \tag{1}$$

where Y_t is the final output, X_t represents traditional technology, μ is a distribution parameter for the traditional productive factors versus the new technology, D_t is the autonomous capital, and υ measures the substitution between the traditional production technology and the new technology. The elasticity of substitution between traditional and autonomous technologies is defined as $\sigma = 1/(1-\upsilon)$.

The traditional technology is represented by another CES function:

$$X_t = \left[\alpha K_t^{\theta} + (1-\alpha)\, L_t^{\theta}\right]^{\frac{1}{\theta}} \tag{2}$$

where K_t is the traditional capital, L_t is labor, α is a distribution parameter of inputs and θ measures the substitution between traditional capital and labor. The elasticity of substitution is defined as $\varepsilon = 1/(1-\theta)$. Empirical evidence suggests that $\varepsilon < 1$ (Chirinko, 2008; Eden and Gaggl, 2018), and that $\sigma > 1$ (DeCanio, 2016; Acemoglu and Restrepo, 2019; Lin and Weise, 2019). Therefore, it is assumed that $0 < \varepsilon < 1 < \sigma < \infty$. This implies higher complementarity between traditional capital and labor than between traditional technology and the autonomous capital. That is, autonomous capital is a substitute for both traditional capital and labor.[4]

[4]For additional information about the characteristics of the production function, see Casas and Torres (2021)

Firms maximize profits in a competitive environment taken factor prices as given, solving the following static maximization problem at each period:

$$\max \Pi_t = Y_t - (1+\tau_t^{sse}) W_t L_t - R_{k,t} K_t - R_{d,t} D_t \tag{3}$$

where W_t is the wage, τ_t^{sse} are social security contributions paid by the employer, and $R_{k,t}$ and $R_{d,t}$ are the returns to traditional and autonomous capital, respectively. From the first order conditions of the firm's profit maximization problem, we obtain the following marginal productivity of each of the three productive factors:

$$R_{k,t} = \alpha \mu Y_t^{1-\upsilon} X_t^{\upsilon-\theta} {K_t}^{\theta-1} \tag{4}$$

$$(1+\tau_t^{sse}) W_t = (1-\alpha)\, \mu Y_t^{1-\upsilon} X_t^{\upsilon-\theta} {L_t}^{\theta-1} \tag{5}$$

$$R_{d,t} = (1-\mu)\, Y_t^{1-\upsilon} {D_t}^{\upsilon-1} \tag{6}$$

where the Euler Theorem holds, profits are zero and output is distributed among the three productive factors, given the assumptions of a competitive market and constant returns to scale.

3.2. Households

We assume that the utility function of our representative household is as follows:

$$U(C_t, L_t) = \gamma \log C_t + (1-\gamma) \log(1-L_t) \tag{7}$$

where C_t is total consumption and γ is a parameter reflecting the willingness to sacrifice units of consumption in favor of leisure time. Total available time has been normalized to one, so leisure is defined as $1 - L_t$, where $0 < L_t < 1$. The representative household satisfies the following budget constraint:

$$\begin{aligned}(1+\tau_t^c) C_t + I_t \;=\; & (1-\tau_t^l-\tau_t^{ssw}) W_t L_t + \\ & (1-\tau_t^k)(R_{k,t} K_t + R_{d,t} D_t) + \tau_t^k (\delta_k K_t + \delta_d D_t) + T_t\end{aligned} \tag{8}$$

where I is the total investment in capital, τ_t^c is a consumption tax, τ_t^l is labor income tax, τ_t^{ssw} is employees' social security contributions, τ_t^k is the capital income tax, T_t is a lump-sum transfer, and δ_k and δ_d are depreciation rates for traditional and autonomous capital, respectively. As we assume an unique total investment instead of specific investment decisions, we have an unique capital accumulation process presented in the following way:

$$I_t = D_{t+1} - (1-\delta_d) D_t + K_{t+1} - (1-\delta_k) K_t \tag{9}$$

The maximization problem faced by the infinity-lived representative household with perfect-foresight is given by,

$$\max_{\{C_t,L_t\}} \sum_{t=0}^{\infty} \beta^t \left[\gamma \log C_t + (1-\gamma)\log(1-L_t)\right] \tag{10}$$

subject to restrictions (8) and (9), where K_0 and D_0 are given, and where β is the intertemporal discount factor.

Equilibrium conditions, representing Euler equations, from the household's maximization problem are,

$$(1+\tau_t^c)C_t = \frac{\gamma}{1-\gamma}(1-L_t)W_t(1-\tau_t^l-\tau_t^{ssw}) \tag{11}$$

$$1 = \beta\frac{(1+\tau_t^c)C_t}{(1+\tau_{t+1}^c)C_{t+1}}\left((1-\tau_{t+1}^k)(R_{k,t+1}-\delta_k)+1\right) \tag{12}$$

$$1 = \beta\frac{(1+\tau_t^c)C_t}{(1+\tau_{t+1}^c)C_{t+1}}\left((1-\tau_{t+1}^k)(R_{d,t+1}-\delta_d)+1\right) \tag{13}$$

representing the optimal labor supply, the investment decision on traditional capital and the investment decision on autonomous capital, respectively. Notice that these equilibrium conditions establish a direct relationship between depreciation rates and returns of both traditional and autonomous capital, as net marginal productivities are equal, such as:

$$R_d - \delta_d = R_k - \delta_k \tag{14}$$

3.3. Government

The government uses tax revenues to finance lump-sum transfers. We assume that the government balances its budget period-by-period by returning revenues from distortionary taxes to the agents via lump-sum transfers. Total tax collection is specified as follows:

$$T_t = \tau_t^c C_t + (\tau_t^l + \tau_t^{ssw} + \tau_t^{sse})W_t L_t + \tau_t^k((R_{k,t}-\delta_k)K_t + (R_{d,t}-\delta_d)D_t) \tag{15}$$

where T_t represents fiscal revenues.

4. Calibration

The model is calibrated according to an artificial economy using standard values in the literature. Given the specification of the model, the combination of traditional and autonomous technologies is a CES function, where the distribution parameter represents the relative weight of each technology in the economy. We use this distribution parameter of the CES production function as a free parameter representing the penetration of autonomous capital in the economy. The autonomous technology adoption rate, represented by $1-\mu$, takes values from 0 to 0.45, where the maximum value is consistent with the estimations about the percentage of tasks in the economy that are potentially automatized by leveraging current technology (Manyika *et al.*, 2017).

As the elasticity of substitution between technologies, $\sigma = 1/(1-\upsilon)$, involves traditional labor and capital on one side and autonomous capital in the other one, it results logical to examine elasticities of substitution lower than the 2.5 estimated by DeCanio (2015). Therefore, we set $\sigma = 2$ and then we provide a sensitivity analysis for the elasticity of substitution in a range from 1 to 5, which implies a range of values for υ between 0 and 0.8. The range of values selected for the sensitivity analysis of this parameter is coherent due to the wide range of values used in the literature. For example, while some authors interpret that robots and labor are perfect substitutes (Acemoglu and Restrepo, 2020) and other authors establish a high elasticity of substitution equal to five (Lin and Weise, 2019), Decanio (2015) estimate this value at 2.5.

The autonomous capital depreciation rate is another key parameter in our model since it determines the relationship between the (gross) returns of the two type of capital. We fixed it to $\delta_d = 0.20$ annually, according to the depreciation rate traditionally assumed for R&D capital. This percentage is reflected in the EU KLEMS data and has been documented by numerous authors (see, for example, Hall, 2005). This calibration is close to Lin and Weise (2019), that along with Krusell *et al.*, (2000), set out a quarterly depreciation of robots at 0.0515. Graetz and Michaels (2018) set a slightly lower robots depreciation rate of ten per cent. Abeliansky and Prettner (2017), following Graetz and Michaels (2018), also assume a robotic depreciation rate of 10%. This depreciation rate would be higher than the one established by the International Federation of Robotics (2016), which sets a lifetime horizon of 12 years for robots.

Tax rates are calibrated according to the OECD average (OECD, 2018; OECD, 2019). Tax rates are fixed to $\tau^c = 0.1832$, $\tau^l = 0.1646$, $\tau^{sse} = 0.1589$, $\tau^{ssw} = 0.0945$ and $\tau^k = 0.2418$. The rest of the parameters are calibrated as standard in literature. As we focus on the long-run, the time dimensional parameters of the model are calibrated in an annual basis. Therefore, we fix $\beta = 0.975$, $\gamma = 0.4$, $\alpha = 0.35$, $\delta_k = 0.06$, and $\varepsilon = 1/(1-\theta) = 0.90$, consistent with Chirinko (2008), Eden and Gaggl (2018) and Lin and Weise (2019).

Table 1 summarizes the benchmark calibration of the parameters of the model and the range of values for the parameter representing the level of automation of the economy.

TABLE 1: Calibrated parameters

	Parameter	Definition	Value
Preferences	β	Discount factor	0.975
	γ	Consumption-leisure preference parameter	0.40
Technology	α	Capital share in the traditional technology	0.35
	δ_k	Traditional capital depreciation rate	0.06
	δ_d	autonomous capital depreciation rate	0.20
	ε	Traditional capital-labor elasticity	0.90
	σ	Traditional-autonomous technologies elasticity	2.00
	μ	Technologies distribution parameter	[0.55-1.00]
Tax rates	τ^c	Consumption tax rate	0.1832
	τ^l	Labor income tax rate	0.1646
	τ^{sse}	Employer's social security tax rate	0.1589
	τ^{ssw}	Employee's social security tax rate	0.0945
	τ^k	Capital income tax rate	0.2418

5. Quantitative results

In this section, we quantitatively measure the implications of automation on the size of the government. We simulate an increase in automation represented by a decline in the aggregate CES distribution parameter μ. A value of $\mu = 1$ indicates an economy with no autonomous capital. We compute a sequence of steady states by reducing the value of this parameter until a value such as labor goes to zero. resulting in a maximum value for the automation rate of 0.45. Figure 1 plots the steady state values of key variables as a function of the automation rate. For relative low values of automation (automation rates below 0.3), steady state output remains almost constant and even reduces, although some significant changes are observed in labor and traditional capital. As we can observe, long-run output increases as the automation rate becomes higher, once the autonomous capital adoption rate is above 0.3. However, the increase in production is not distributed equally between consumption and investment. Automation changes the distribution share of consumption and investment to output, decreasing the consumption-output rate and increasing the investment-output rate, due to the higher depreciation rate of autonomous capital. Indeed, consumption decreases in the first stages of automation, as more income must be allocated to investment spending to finance autonomous capital consumption, given that the depreciation rate of autonomous capital is higher than the depreciation rate of traditional capital. Again, only for a large enough autonomous capital adoption rate the increase in output can finance both consumption and the higher investment in the long-run. The changes produced in steady state output, consumption and investment are consequence of the substitution among the three production inputs. Autonomous capital stock increases exponentially while traditional capital stock plots a U-shape, decreasing in the first stages of automation and then increasing once the proportion of autonomous capital is large enough.

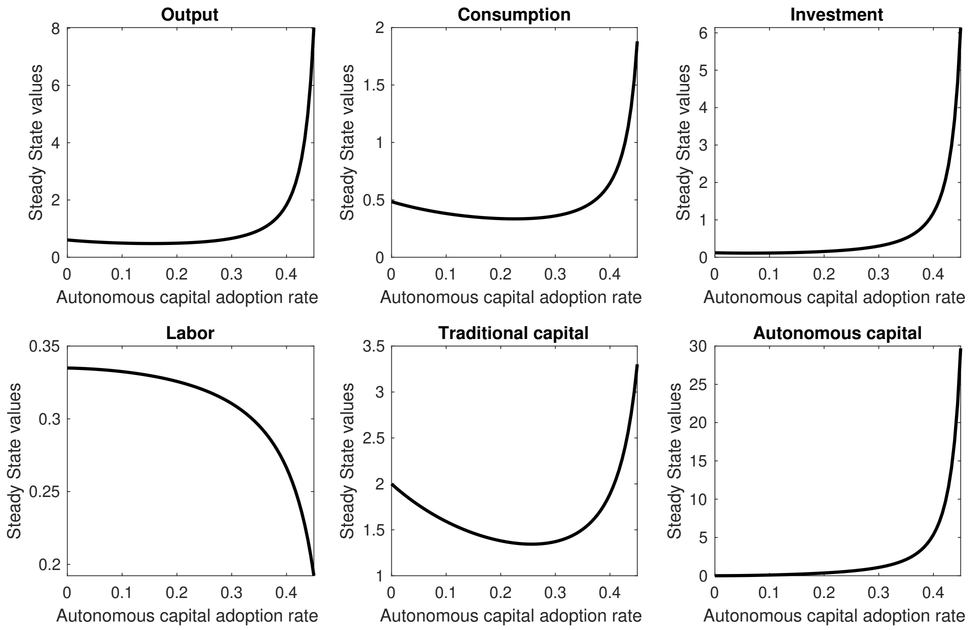

FIGURE 1: Steady state values of key macroeconomic variables as a function of automation

The most dramatic effect of automation is found in the reaction of labor. Automation reduces working hours no matter how the rate of penetration of autonomous capital is.[5] Whereas for low values of automation the negative effects on working hours is relatively small, the substitution effects increases as automation becomes higher. What is clear from the results showed by Figure 1, is that automation will change the relative importance of inputs in production and hence, the way how income is generated and distributed in the economy, shifting the tax base from labor to capital. These changes are expected to have a direct impact on public finance depending on the tax mix. We explore three scenarios:

[5]Labor represents working hours in our economy model. The decline in working hours provoked by automation can also be interpreted as a reduction in the workday and not in employment (see Bongers and Molinari, 2020).

(i) how specific tax revenues change with automation given the baseline tax mix; (ii) how taxes rates should be changed to keep fixed tax-specific revenues; and (iii) what should be the capital income tax rate, keeping fixed the other taxes, to keep constant the size of the government.

5.1. Experiment 1: Automation with fixed tax rates

The first experiment consists in computing fiscal revenues to output ratio (total and tax-specific) as a function of the automation rate keeping fixed the tax rates to the baseline calibration. Results from this experiment are plotted in Figure 2. As we can appreciate, the size of the government in the baseline calibration would be 42% in a world without autonomous capital (a production function with only labor and traditional capital). The introduction of the autonomous technology pushes down the government size steadily. When the autonomous capital adoption rate reaches the maximum value of 0.45, the size of the government falls to only 11%. This large fall in the total tax revenues to output ratio find its explanation in the fall of revenues to output ratio from all taxes except for the capital income tax. Notice that even revenues from the consumption tax as a fraction of output decline as a consequence of the required higher investment rate as automation increases. That is, automation increases the investment to output ratio and decreases the consumption to output ratio. In particular, fiscal revenues as a percentage from output levied by the consumption tax goes down from 15% to 5%.

A similar loss of fiscal revenues is found for all payroll taxes on labor income (social security contributions and the labor income tax). The observed decline in labor payroll taxes revenues is even more dramatic. Collected revenues from the labor tax to output ratio goes from around 10% to 1%, and total social security contributions to output ratio goes from around 15% to 2%. Thus, automation would not only reduce tax revenues from labor but also could call into cuestion the sostenibility of pay-as-you-go social security scheme. The only tax that contributes to increases fiscal revenues is the capital income tax. As we observe in the last row of the figure, capital income tax revenues to output ratio increases from 2.7% to 3.3%. This is explained by the increase in the autonomous capital income tax collection to output ratio that compensates and exceeds the drop of the traditional capital income tax collection. However, fiscal revenues from capital income tax represents a small fraction of total fiscal revenues and cannot compensate the decline in fiscal revenues from the other sources.

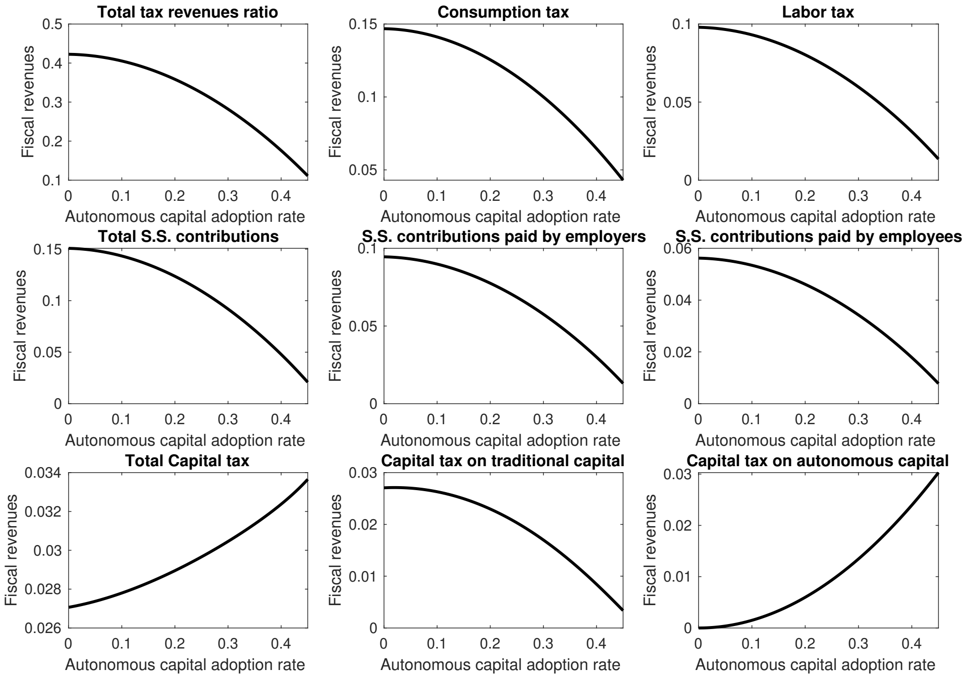

FIGURE 2: Steady state values for the ratio of tax revenues to output as function of the autonomous capital adoption rate.

Two key implications can be obtained from previous results. First, while it is logical that in the face of an increase in production, total tax collection will be increased by the expansion of the economy, we find that the automation process causes fiscal revenues to output ratios to collapse. That is, the expansion of the economy exceeds the expansion of public finance. To a large extent, we could say that the penetration of the new autonomous technology causes tax revenues from traditional sources to fall. On the other hand, the expansion of output does not imply equal increases in consumption and investment, but since the expansion of the economy is driven by a new technology with a high depreciation rate, more resources are needed to be allocated to investment, causing the ratio of fiscal revenues from consumption to output to fall as well. Second, the size of the government cannot be maintained with automation and the current tax mix. This is because output expansion far exceeds the expansion of public revenues, which are decreasing in relation to the output as the autonomous capital share increases. This would force the government to increase tax rates parallel to automation. Furthermore, automation changes the functional distribution on income increasing the capital share, which call for a reform of the tax mix.

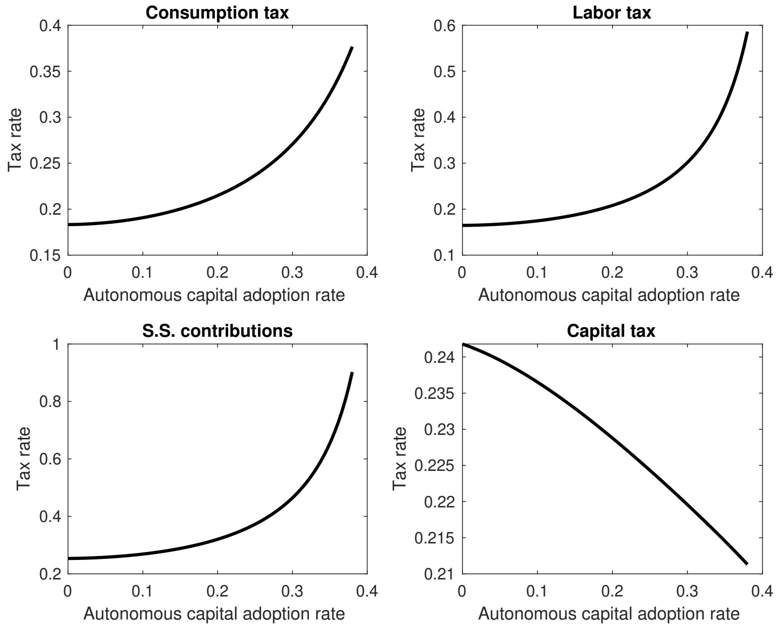

FIGURE 3: Tax rates as a function of the autonomous capital adoption rate to keep constant specific-fiscal revenues.

5.2. Experiment 2: Automation with fixed tax-specific revenues

One lesson we learn from experiment 1 is that the current government size is not sustainable with the current tax mix as the automation process progresses. This means that current tax rates should be modified according to the observed changes in the tax bases. Next, we consider an scenario in which specific tax rates are changed to keep fixed the tax burden. This counterfactual experiment would indicate how taxation policy should adapt to the automation process, depending on the changes in the combination of inputs and how income is generated and spent, in order to keep constant the size of the government. Estimated tax rates as a function of the automation rate are shown in Figure 3. As we can observe, as automation increases, all tax rates, except the capital income tax rate, should be increased. Specifically, when the adoption rate of autonomous technology reaches the 38%,[6] the consumption tax rate should be 0.3764, the labor income tax rate should be 0.5862, and the total social security contributions tax rate should be 0.9024 in order to keep constant the government size. By contrast, the capital income tax rate should be lower as the accumulation of autonomous capital is fairly enough to keep constant capital income. In this

[6]This is the maximum value for $1 - \mu$ consistent with the baseline government size with no automation before labor collapses to zero.

sense, the policy of fixed tax-specific revenues would deepen the income inequality increase caused by automation.[7]

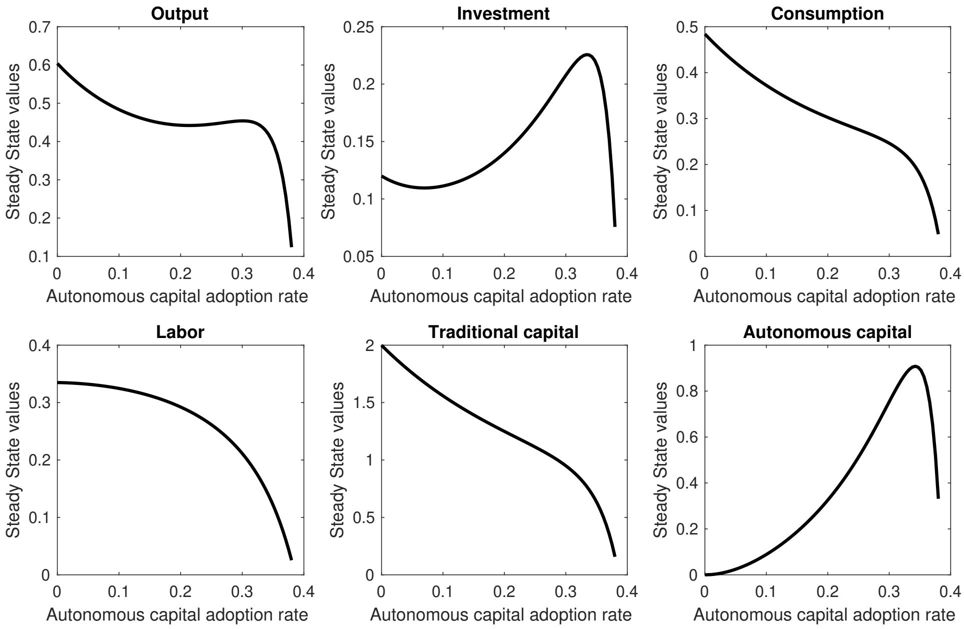

FIGURE 4: Steady state for key aggregate variables as a function of the autonomous capital adoption rate in a scenario with fixed tax-specific revenues.

However, such fiscal policy could be impractical and counterproductive. Indeed, estimated increase in the tax rates to keep constant fiscal revenues are of a large magnitude, increasing distortions in the economy and causing a negative impact on economic activity. Figure 4 plots the steady state values of the key macroeconomic variables resulting from the previous tax policy. These figures plot the steady state values for the key variables as a function of the autonomous capital adoption rate and the new taxes rates needed to keep constant the size of the government. As we can observe, this fiscal tax policy makes output to decrease. This fall is accompanied by a decrease in consumption, labor and traditional capital, while investment and autonomous capital increase before the collapse of labor once automation rate is above 35%. Therefore, this fiscal policy aimed to keep constant the share of each tax revenues is not a solution in the face of automation. By contrast, this tax policy would accelerate the collapse of the economy (reducing labor to zero) given the higher labor payroll taxes in combination with a higher consumption tax.

[7]See, for instance, Lankisch *et al.*, (2019) and Jaimovich *et al.*, (2021).

The lesson we can extract from this analysis is that the current tax menu cannot be maintained in an environment with high automation and it should be accommodated to the new income generation scenario, where production technology is increasingly dominated by autonomous capital. However, this analysis reveals some insights of how the advance of automation can be directed by fiscal policy.

5.3. Experiment 3: Capital income tax to keep fixed total fiscal revenues

Finally, we study a scenario in which only the capital income tax is modified to compensate for all the effects of automation on public finance. In this counterfactual experiment the consumption and labor income tax rates and the social security contributions rate remain fixed to the baseline calibration values. This experiment is motivated by previous results. First, automation will transform the combination of inputs used in the economy where automatic capital will substitute both traditional capital and labor. In short, automation will increases capital deepening while reducing labor. This changes the functional distribution of income, reducing the labor share and increasing the capital share. Additionally, automation would increase the investment to output ratio and thus decreasing the consumption to output rate. Therefore, capital income would be transformed into the main tax base replacing both labor income and consumption tax bases.

Previous studies have already explore reasons for the optimality of differential capital taxation. In particular, Slavik and Yazici (2014), setting the focus on the marginal tax rates on returns to capital assets, conclude that it is optimal to tax equipment capital at a higher rate than structures capital. In a quantitative exercise, these authors state that the optimal tax rate on equipment capital is at least 27 percentage points higher than the optimal tax rate on structure capital. Contrary to this idea, we can also find authors defending that capital should not be tax (Chari *et al.*, 2020). Indeed, one alternative would be to consider two specific taxes for traditional and the autonomous capital. However, this would be difficult for practical implementation, as first we should have a clear definition of what traditional and autonomous capital are, and second, how to distinguish between income produced by each capital. Instead, in this experiment we maintain the assumption that the capital income tax rate is the same for all types of capital.

Figure 5 plots the estimated capital income tax rate as a function of automation that would be required to keep constant the government size. As we can observe, the value of this tax rapidly increase as the autonomous technology gains weight in the aggregate production. We find a S-shaped relationship between the capital tax and automation, resulting in considerably high values for the tax rate. For the maximum automatic capital adoption rate used in the simulation, the tax rate on capital income would be around 80%. At a first sight, this is a substantial value. However, it is also true that the capital income becomes the main tax base of the economy as a consequence of automation.

We now turn to study the impact of this capital income tax rate on the rest of the economy. Figure 6 plots the key steady state values of the economy as a function of the new capital income tax that keeps fixed the government size. The consequences of this increasing capital income tax rate are remarkable and different to the previous scenario. In particular, under the implementation of this capital income tax rate policy, output, investment and consumption describe U shapes as autonomous technology advances and autonomous capital stock increases while traditional capital decrease. This progressive higher capital tax rate reduces capital deepening in the economy. Indeed, steady-state output is reduced for the initial stages of automation. However, even with an increasing capital income tax rate, autonomous capital is accumulated at a high rate. On the other hand, labor displacement is significantly less intensive under this fiscal scenario compared to the previous one. The increasing capital income tax reduces net income from capital, slowing the substitution of labor by autonomous capital.

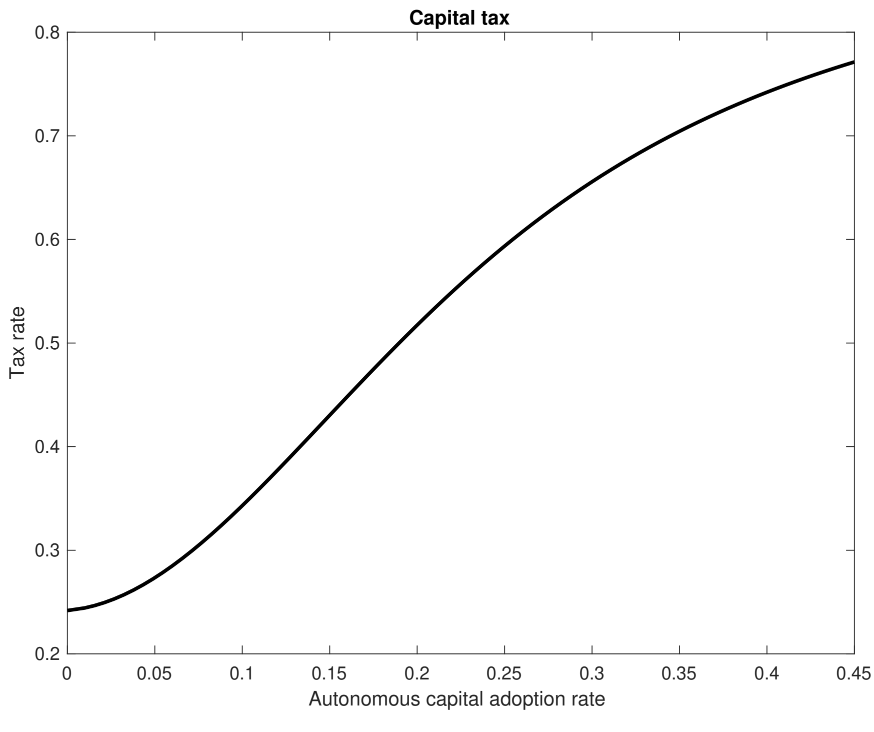

FIGURE 5: Capital income tax rate to keep constant fiscal revenues as function of the autonomous capital adoption rate.

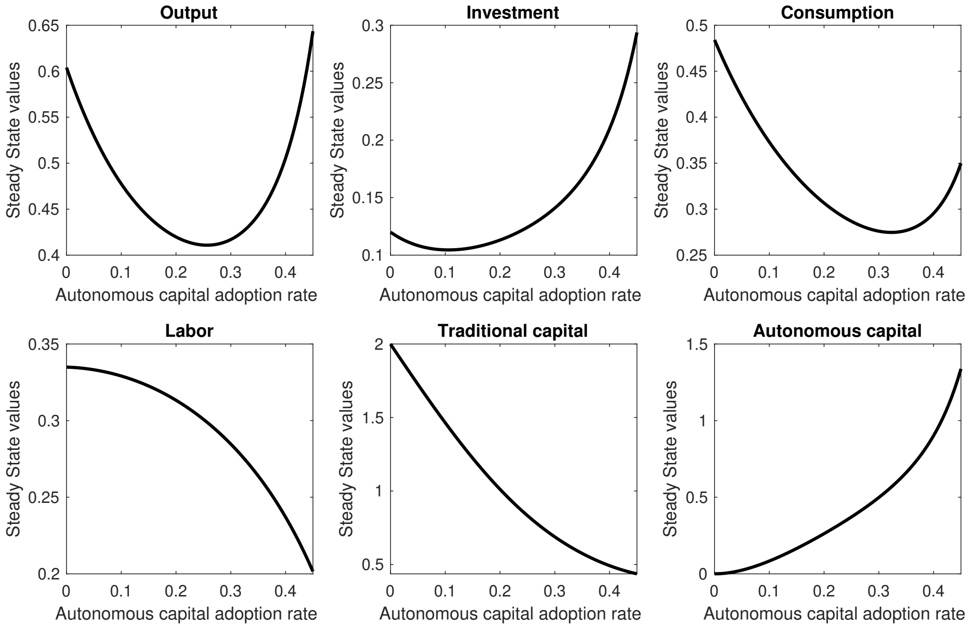

FIGURE 6: Steady state values as function of the autonomous capital adoptionrate in a scenario with a capital income tax rate to keep fixed the government size.

It is interesting to compare the results plotted in Figure 6 with Figure 4. In both cases, the size of the government is kept constant for any level of autonomous capital adoption and the only difference is in the tax policy regime. Whereas in Figure 6 the size of the government is kept constant by changing only the capital income tax rate, whereas in Figure 4 all tax rates are changed by keeping constant fiscal revenues from each source. Differences of both fiscal policy scenarios are significant. In the first case, traditional capital and labor will be substituted by autonomous capital, but as the automation process increases, the effect on output, investment and consumption turns out to be positive for high values of automation. By contrast, changing all tax rates would lead to a collapse of the economy when the automation capital adoption rate is close to 40%. What these results show is that it turns out less distorting increasing the capital income tax to keep fixed the size of the government, that an alternative fiscal policy that keep constant revenues from each tax.

6. Sensitivity analysis

In this section we carry out a sensitivity analysis regarding two key aspects of the automation process. On the one hand, due to the lack of consensus and empirical evidence on the elasticity of substitution between traditional technology and new technology, we repeat the simulations for a range of values of the elasticity of substitution from 1 to 5. On the other hand, we repeat the simulation using an alternative specification of the production function widely used in the literature. This alternative specification assumes that this new technology replaces human labor, contrary to the model presented in this paper which assume that the autonomous capital is substitute of both traditional capital and labor.

6.1. Elasticity of substitution between technologies

First, we study the sensitivity of the results to alternative values of the elasticity of substitution between the traditional and the autonomous technologies. In Figure 7, we present all taxes collection as a percentage of output for three alternatives values of the elasticity of substitution (1, 2, and 5). We can observe that differences are small for low values of the autonomous capital adoption rate. However, for higher values of automation, results are more sensitive to the elasticity of substitution. As the elasticity of substitution increases, automation has a greater impact, accelerating the decline of the government size. For all the three elasticities values investigated we find a negative relationship between automation and the government size.

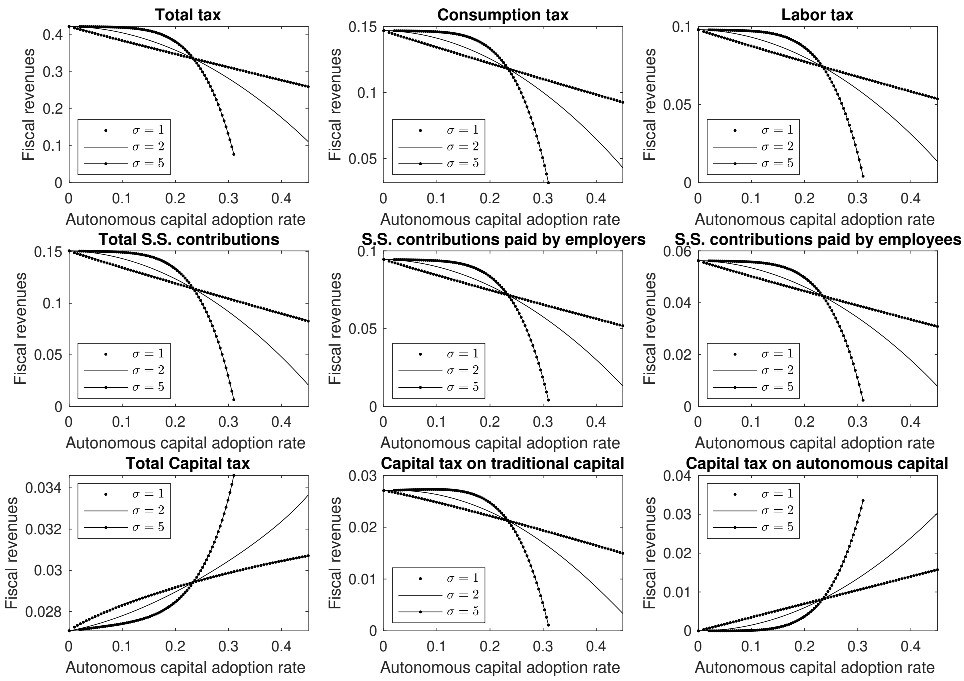

FIGURE 7: Fiscal revenues as a percentage of GDP as function of the autonomous capital adoption rate and the elasticity of substitution between traditional technology and autonomous technology.

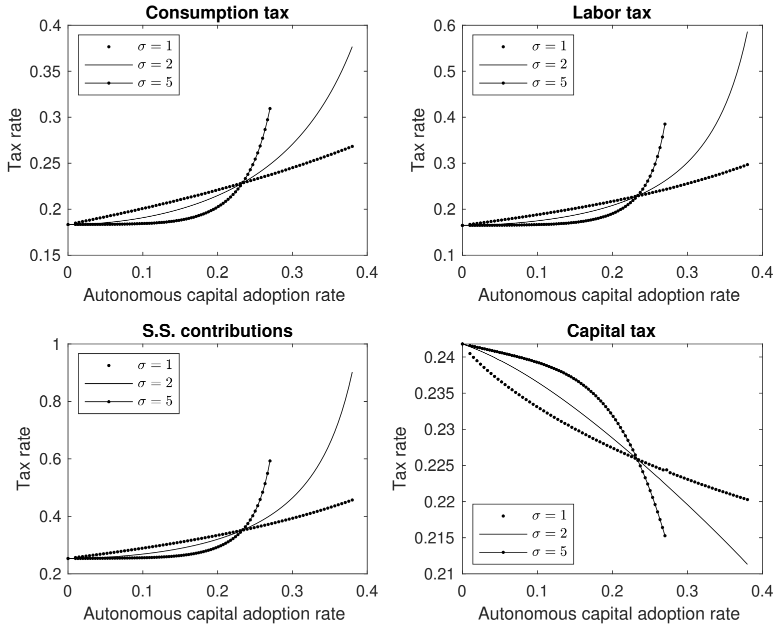

FIGURE 8: Tax rates to keep constant fiscal revenues as function of the autonomous capital adoption rate and the elasticity of substitution between technology.

Next, we carried out a sensitivity analysis on experiment 2 to investigate how sensitive are the estimated tax rates required to keep constant fiscal revenues depending on the elasticity of substitution. Results from this sensitivity analysis are plotted in Figure 8. We find that the elasticity of substitution has an impact on the required tax rates, but in all the cases tax rates must be changed in the same direction. The consumption, labor income and social security contributions tax rates increases with automation, whereas the capital income tax rate reduces with automation.

Estimated tax rates depends on the automation rate. For low values of automation (below a automation adoption rate of 22.5%), tax rates are almost constant for the highest value of the elasticity. However, this effect reverse for values of the automation rate above 22.5%. In this case, the greater the elasticity of substitution between technologies is, the greater the negative impact of automation on the government size and thus it is needed a larger increase in the tax rates.

Finally, we repeat experiment 3 for the selected values of the elasticity of substitution. Figure 9 plots the implicit capital income tax rate required to keep fixed total fiscal revenues as a function of the elasticity of substitution. For the three values of the elasticity we find a increasing trend in the tax rate, with similar values. For an automation rate of 40%, the capital income tax rate should be in a range of 0.65 to 0.80, for the lower and higher elasticity of substitution, respectively.

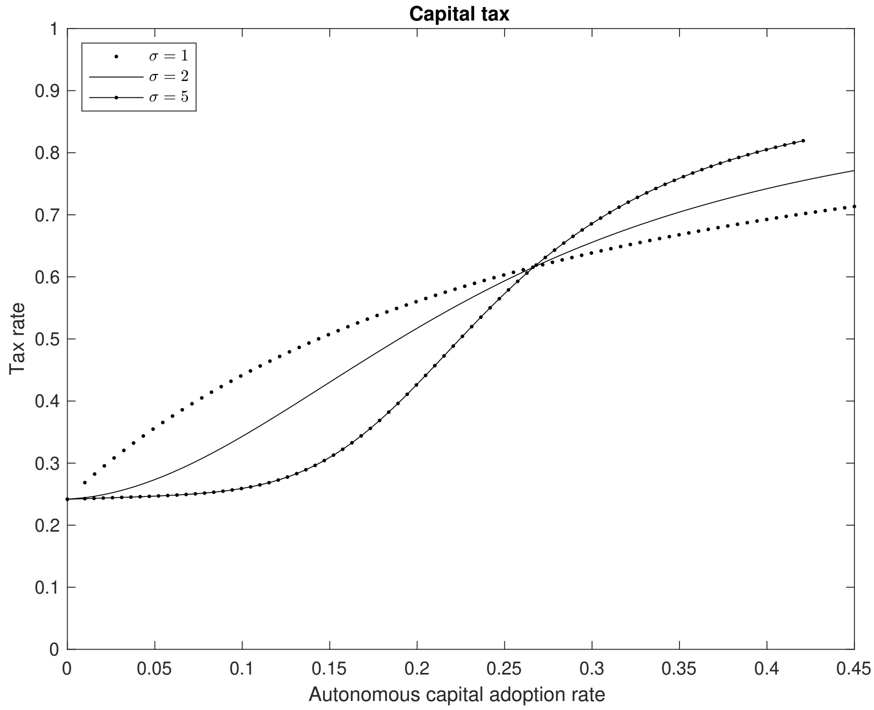

FIGURE 9: Capital income tax rate to keep constant fiscal revenues as function of the autonomous capital adoption rate and the elasticity of substitution.

6.2. Alternative technology

The model used in this paper assumes that robots and AI are a new type of capital (autonomous capital) that can substitute both traditional capital and labor. This assumption is based on the characteristics of new autonomous capital, a combination of robots and AI that can perform task in an autonomous way. In this section, we repeat the previous analysis using the standard production function specification with robots widely used the literature. This specification consists of assuming that robots replace workers while complementing traditional capital units. This is the technology specification assumed by, for example, in Eden and Gaggl (2018), Berg *et al.* (2018), and Lin and Weise (2019). Under this assumption, the production function would be as follows:

$$Y_t = \left[\mu X_t^{\upsilon} + (1-\mu)\, K_t{}^{\upsilon}\right]^{\frac{1}{\upsilon}} \tag{16}$$

where Y_t is the final output, μ is the CES distribution parameter, X_t is a composite of human labor and robots, K_t is the traditional capital, and υ measures the substitution between the traditional capital and labor -human or robotic-. The elasticity of substitution between traditional capital and labor -human or robotic- is defined as $\sigma = 1/(1-\upsilon)$. X_t represents labor tasks performed by autonomous capital and/or human labor:

$$X_t = \left[\alpha D_t^{\theta} + (1-\alpha) L_t^{\theta}\right]^{\frac{1}{\theta}} \tag{17}$$

where D_t is the autonomous capital, L_t is labor, α is a distribution parameter of inputs and θ determines the elasticity substitution between robotic and human labor. The elasticity of substitution is defined as $\varepsilon = 1/(1-\theta)$. For simulating this technology, we assume that the parameter σ takes a value of 0.90 while ε take values between 1 and 5. Similarly, the parameter μ takes a value of 0.65 while α, the new adoption rate, takes values from 0 to 0.45, as in previous simulation. Using this new production function, we repeat the analysis carried out previously to check how sensitive are results to an alternative specification of the technology.

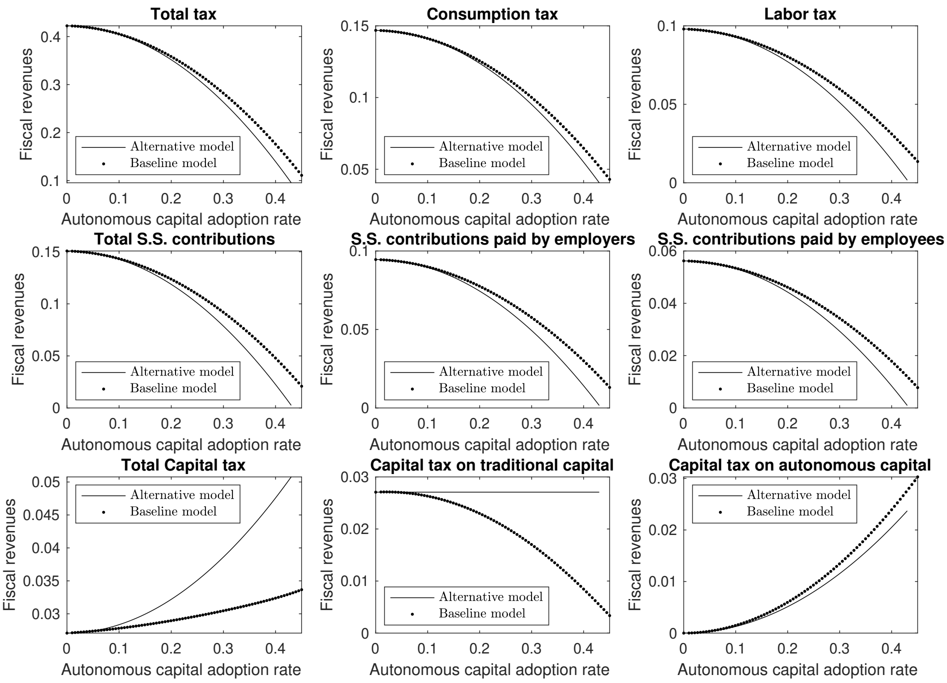

FIGURE 10: Fiscal revenues as a function of the autonomous capital adoption rate. Alternative production function specification.

Figure 10 plots the relationship between fiscal revenues and the automation rate. It can be observed that the results from the production function specification are almost equal than the ones obtained from the baseline model. That is, the two production functions predict the same relationship between automation and the size of the government; a drop in fiscal revenues as a percentage of output, except for the revenues from the capital income tax. The main difference is found regarding the traditional capital income tax revenues which remains constant with this alternative specification.

Again, the repetition of experiment 2 leads to similar results (Figure 11). As a consequence of automation, consumption and payroll tax rates should be increased to keep fixed fiscal revenues from this taxes, whereas the capital income tax would be reduced. Comparing Figure 11 with Figure 3, we find that required changes in tax rates are slightly less sensitive to automation

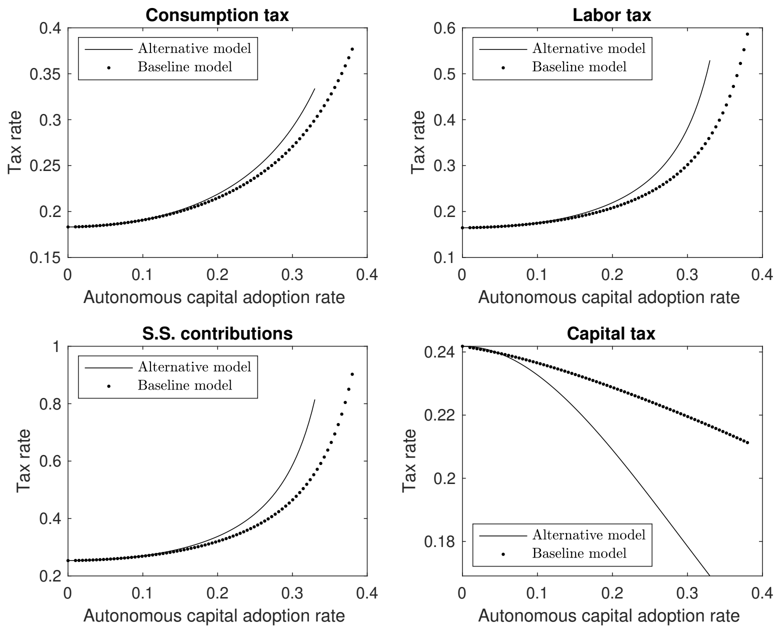

FIGURE 11: Tax rates to keep constant fiscal revenues as a function of the autonomous capital adoption rate. Alternative production function specification.

Finally, we repeat experiment 3 using this alternative production function specification. The estimated capital income tax required to keep constant the size of the government as a function of the automation rate is presented in Figure 12. We find a similar relationship between the automation rate and the tax rate to the one found in the previous analysis. Estimated values for the tax rate are slightly lower than the estimated using the model presented in the paper, but of similar magnitude. For an automation rate of 0.45%, the required capital income tax rate would be around 0.72, compared to a tax rate of 0.77 in the baseline model. Therefore, we conclude that results of the simulation are robust to the particular specification of the production function.

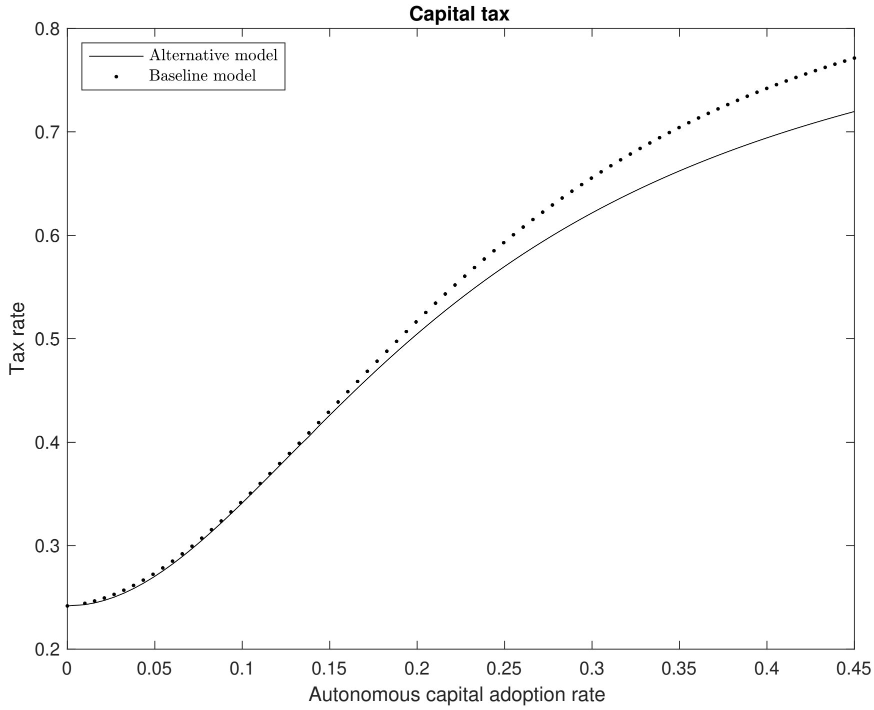

FIGURE 12: Capital income tax rate to keep constant fiscal revenues as a function of the autonomous capital adoption rate. Alternative production function specification.

7. Concluding remarks

Recent advances in robotization and AI open a new era for humankind by introducing a disruptive technology with dramatic consequences on the economy. This paper focuses on the implications of automation for the size of the government, measured as the tax revenues to output ratio. We find that automation significantly affects public finance given its impact on the combination of inputs used for production activities. Automation will have positive effects on the macroeconomy, but transforming production in a more capital intensive technology. Given that current tax systems are based heavily on taxing labor income, substitution of labor by the new autonomous capital will have a dramatic impact on fiscal revenues.

Under the current tax mix scenario, automation will expand final output, with a positive impact on all macroeconomic variables, except labor. We find three important results.

First, the steady-state ratio of consumption to output decreases with automation. This is because automation implies a higher autonomous capital deepening with a higher depreciation rate compared to the traditional capital assets, resulting in a highter steady-state investment ratio. Therefore, more resources are needed to be devoted to replace depreciated autonomous capital which reduces the ratio of consumption to output. Second, total fiscal revenues increases with automation given the expansion of the economy. However, the relative contribution of the different sources of fiscal income changes. The proportion of fiscal revenues from capital increases, whereas the proportion of fiscal revenues from labor income and consumption declines. However, the size of the government, measured as the steady-state ratio of fiscal revenues to output (assumed to be equal to the ratio of government spending to output), declines with automation.

To explore the consequences of automation on the size of the government we proceed as follows. First, we analyze the evolution of fiscal revenues as a fraction of output from each tax as a function of automation, keeping constant the current tax mix. The automation process affects the composition of fiscal revenues, changing the contribution shares of taxes. In particular, the labor tax and the social security contributions progressively diminish their contribution shares in favor of taxating on capital. The most important result is that the size of the government decreases with automation. Thus, automation will be an important source of deterioration of public finance stopping the observed trend in the last century of a steady increase in the size of governments in advanced economies.

Given the previous results, we proceed to study how tax rates should be changed to keep constant fiscal revenues. We conduct this experiment tax by tax. We find that all taxes rates should be significantly increased, except the capital income tax. However, estimated taxes rates turn out to be extremely high, increasing distortions on the economy. Moreover, this new tax policy would eliminate the positive impact of automation on the economy, even accelerating the decline in labor as distortions on the optimal behavior of households would be also increasing. In sum, the rise in taxes rates to compensate the effects of automation on the fiscal revenues to output ratio is not a practical option, and a redesign of the tax system is compultory.

Therefore, we conduct a third experiment which consist in estimating the capital income tax rate that keep fixed total fiscal revenues. If capital is the most important input producing income, the tax policy should accommodate to automation by increasing capital income taxes. We find that capital income tax rate would reach a value close to 80% for an automation rate of 45%. This fiscal policy would have less distortionary effects on the economy mitigating the negative effects of automation on labor, although would cancel out the positive effect of automation on final output.

A sensitivity analysis reveals that previous results are robust to different values of the elasticity of substitution between technologies, and to alternative specifications of the production technology.

In summary, two main results derives from this paper. First, automation without a deep fiscal reform will stop the observed increasing trend in the government size in the economy. Second, automation will put at risk social security sustainability in pay-as-you-go systems. These results contribute with new evidence to the debate among scholars about the necessity to carry out profound tax policy reforms to accomodate the impact of automation.

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