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LABOUR TAXES, MARKET SIZE AND PRODUCTIVITY GROWTH*

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How do changes in labour taxes affect innovation and aggregate productivity growth? To answer this question, we propose a quantitative, general equilibrium growth model featuring product and quality innovation with endogenous market structure, estimate its parameters and provide empirical validation for the propagation mechanism of labour tax changes. We find that a temporary cut in flat-rate labour taxes produces a growth acceleration in aggregate productivity, permanently increasing the path of real GDP per capita. Moreover, such permanent gains are sizeable even without long-run growth effects.

How do changes in labour tax rates affect innovation and aggregate productivity growth? We use a quantitative, general equilibrium model with product and quality innovation to answer this question, estimate its parameters and provide empirical validation for the propagation mechanism. Consistent with novel empirical evidence based on narratively identified tax shocks in Section 1, we find that a temporary cut in flat-rate labour taxes produces a productivity growth acceleration in the short run. While this is a transitional dynamics phenomenon, it permanently raises the path of real GDP per capita. Moreover, such permanent gains are sizeable even without long-run growth effects.

Our theoretical analysis rests on three premises. First, changes in flat-rate labour taxes have short-run growth effects, but no long-run growth effects. This premise is the natural starting point, given the well-known empirical observation that individual income tax rates are generally uncorrelated with average growth rates across countries and over time (Easterly and Rebelo, 1993; Stokey and Rebelo, 1995; Mendoza *et al.*, 1997).

The second premise is that, historically, permanent changes in tax rates have been the exception rather than the norm. To be sure, tax rate changes legislated as permanent are frequent; however, a common practice of governments has been to partly or wholly overturn previously enacted tax changes (see Romer and Romer, 2009; 2010 for a history of US tax policy). These patterns have led to substantial variation in marginal tax rates on labour income (Barro and Sahasakul, 1983; Barro and Redlick, 2011). Hence, quantitative exploration of US tax policy requires considering transition dynamics and expectations about future policy changes that need not necessarily reflect those legislated initially.

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Third, labour taxation is by far the largest source of tax revenues in OECD countries.[1] We thus focus on the distortionary effect of labour taxation on work incentives and study how changes in hours worked propagate through the economy. This approach also allows us to capitalise on the extensive empirical literature that estimates the causal effect of tax rate changes on hours worked and real GDP per capita.

In Section 1, we establish new evidence on the propagation mechanism of marginal tax rate shocks in the United States. To gauge the economy's dynamic response to tax changes, we identify tax shocks based on the narrative approach of Romer and Romer (2010), and estimate impulse response functions (IRFs) based on the local projection method of Jordà (2005) and instrumental-variable regressions. In response to a marginal tax rate increase, hours worked fall on impact and revert to their initial level before the shock. These patterns are broadly consistent with existing evidence (see, e.g., Barro and Redlick, 2011 and Mertens and Ravn, 2013). Similarly, the number of firms falls and reverts to its pre-shock level. However, differently from the response of hours worked, the response of the number of firms is hump shaped, with a trough occurring one year after the tax shock. R&D and utilisation-adjusted total factor productivity (TFP) fall, displaying pronounced hump-shaped responses. These empirical findings support the propagation mechanism of tax shocks embodied in the model.

In Section 2, we develop a quantitative version of a Schumpeterian growth model without the 'scale effect' (see Dinopoulos and Thompson, 1998; Peretto, 1998; Segerstrom, 1998; Young, 1998; Howitt, 1999).[2] The absence of the scale effect is critical for the model to be consistent with the lack of growth effects of labour taxation. In addition, the balanced growth path of the model is consistent with two long-run observations for the post-war US economy. One is that per capita hours worked and per capita number of firms exhibit no long-run trend (see, e.g., Laincz and Peretto, 2006 and Cociuba *et al.*, 2018). The second is that measures of R&D intensity are strongly correlated with TFP growth (see, e.g., Zachariadis, 2004; Laincz and Peretto, 2006; Ha and Howitt, 2007; Ulku, 2007; Madsen, 2008 and Ang and Madsen, 2011).

In the model, productivity growth results from product and quality innovation. In free-entry equilibrium, entrants create new products, expanding product variety. In contrast, incumbents make investments to improve the quality of their existing products (see, e.g., Mansfield, 1968; Scherer, 1986; Broda and Weinstein, 2010 and Garcia-Macia *et al.*, 2016 for empirical evidence). Market structure is endogenous: firms' entry and incumbents' production and investment decisions determine the mass of firms and firm size (measured as labour per firm). The number of firms and average product quality is the aggregate state variables that propagate labour tax shocks. A shock to the labour tax, say, a reduction in the labour tax rate, manifests itself as an increase in hours worked, akin to a positive labour supply shock. Such an increase in hours worked is associated with an increase in consumption expenditures, which raises the demand for intermediate goods, expanding the size of the market in which firms operate.

In the short run, the mass of firms rises, but only sluggishly, so an increase in the overall market size is associated with an increased firm size of incumbents, which spurs incumbents' innovative

[1] For example, in the United States, in 2018, individual income taxes, social insurance and retirement receipts are 50.6% and 35.2% of total tax revenues, respectively. The remaining 14.2% is corporate income taxes (6%), excise taxes (2.9%) and other taxes, such as estate, gift taxes, customs duties and fees (5.3%). See the Historical Tables from the Office of Management and Budget at https://www.whitehouse.gov/omb/historical-tables/.

[2] The scale effect refers to the property of early endogenous growth models that the growth rate of the economy is proportional to population size (see Romer, 1990; Grossman and Helpman, 1991 and Aghion and Howitt, 1992). This prediction is problematic because it means that population growth should accelerate per capita real output growth, which is at odds with the evidence.

investments. Because of sunk entry costs, the mass of firms is a state variable and cannot jump on impact in response to the tax shock. The variable that jumps on impact is the flow of new firms. Over the adjustment dynamics to the labour tax shock, the time path of firm size is the key driving force of the intertemporal allocation of aggregate innovative investment. In the long run, the growth effect of labour tax shocks vanishes as the mass of firms adjusts. Such sterilisation holds even in the case of a permanent tax cut. While the economy's growth rate reverts to its level before the tax cut, per capita output remains above its previous trend level forever. This chain of causal links through which changes in labour tax rates impact the economy hinges on the 'market-size effect', a mechanism at the heart of endogenous growth theory.[3]

In Sections 3 and 4, we examine the quantitative predictions of the model for the US economy. To this end, we estimate model parameters by matching salient moments of US data, including the IRFs estimated in Section 1. In the model, as in the data, in response to a temporary cut in the average marginal tax rate, market hours worked and the number of firms per capita rise, with a corresponding acceleration of TFP growth.

After establishing that the model accounts for the empirical IRFs of hours worked, the number of firms, R&D and TFP, we use it to conduct two quantitative experiments. First, we feed to the model the observed marginal tax rates (and government purchases as a share of GDP) and find that the variation in tax rates alone accounts for a non-trivial part of the variability in aggregate variables. Second, we quantify the impact of the Tax Cuts and Jobs Act (TCJA) of 2017. We focus on the provisions in TCJA on the individual income tax. Available estimates point to a sizeable cut in the average marginal personal income tax rate of nearly three percentage points, a magnitude comparable to the tax rate cuts implied by the Revenue Act of 1964 and the Tax Reform Act of 1986 (see Barro and Furman, 2018 and Mertens, 2018). The model predicts that a temporary, three percentage point cut in the average marginal individual income tax rate, set to expire in 2025 as in TCJA, leads to a gradual, sustained acceleration in TFP and labour productivity growth. This temporary growth acceleration translates into a permanent gain in real GDP per capita of 2% relative to a counterfactual economy without the labour tax cut in TCJA.

Our paper contributes to understanding how tax policy changes affect innovation and aggregate productivity growth. It closely relates to the literature that uses endogenous growth models to study the effects of fiscal policy (see, e.g., King and Rebelo, 1990; Rebelo, 1991; Stokey and Rebelo, 1995 and Peretto, 2003; 2007). The challenge faced by the early models of endogenous growth—AK type and models of innovation à la Romer (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992)—was that personal income tax rates were predicted to have implausibly large effects on long-run growth rates. Key to these predictions was the presence of the 'scale effect', whereby small changes in tax rates translate into large differences in growth rates over time and across countries. A consensus has thus emerged that models with the scale effect are largely inadequate for policy evaluation.

Recently, a new wave of papers has taken a quantitative approach to gauge the effects of various government policies in the context of models of endogenous technical change (see, e.g., Cozzi and Impullitti, 2010; Akcigit *et al.*, 2017; Jaimovich and Rebelo, 2017; Atkeson and Burstein, 2019 and Ferraro *et al.*, 2020). Yet, the quantitative implications of these models for the transition dynamics of productivity in general, and its relation to tax policy in particular, have not received much attention.

[3] See Acemoglu and Linn (2004) and Cerda (2007) for evidence on the link between market size and the introduction of new drugs in the US pharmaceutical industry. See also Cohen and Levin (1989) and Cohen (2010) for surveys of the empirical evidence on market structure and innovation.

What distinguishes this paper from the existing ones, including our own, is two-fold. First, we show that the model is consistent with state-of-the-art empirical estimates of the dynamic responses of market hours worked, number of firms, R&D expenditures and TFP to narratively identified tax shocks. This approach provides credibility to the model as a laboratory for counterfactual analysis. Second, we solve for the global non-linear equilibrium dynamics after feeding to the model the observed time series of marginal tax rates and government purchases. We do so because local dynamics around the steady state do not accurately describe the dynamic adjustment of the economy in response to some of the sizeable changes in tax rates observed in the United States, e.g., the Reagan tax cuts of the eighties. Also, some tax rate changes have coincided with changes in government purchases, which arguably shift private sector's expectations about the size of the government. Thus, feeding to the model the observed changes in government purchases alongside those in labour tax rates allows us to gauge the economy's response to changes in tax policy over and above the wealth effect due to changes in the present value of government purchases.

Finally, this paper is also related to the literature that stresses the pro-cyclicality of R&D (see, e.g., Comin and Gertler, 2006; Barlevy, 2007; Anzoategui *et al.*, 2019; Bianchi *et al.*, 2019 and Queralto, 2020). In this literature, cyclical shocks change market size and lead to transitory changes in R&D. In our model, labour tax changes propagate via a market-size channel, too.

1. Evidence on the Effects of Labour Tax Shocks

In this section, we consider US data and establish new evidence on the propagation mechanism of marginal tax rate shocks.[4] We restrict attention to variables describing the propagation mechanism of tax shocks embodied in the model in Section 2, i.e., hours worked, number of firms, investment in research and development (R&D) and TFP. To gauge the dynamic behaviour of these variables in response to tax changes, we identify tax shocks based on the narrative approach of Romer and Romer (2010), and estimate IRFs based on the local projection method of Jordà (2005) and instrumental-variable (IV) regressions (Jordà and Taylor 2016; Ramey 2016).

Our estimates support the model's propagation mechanism of labour tax changes. All variables, but per capita hours worked display hump-shaped responses. First, in response to a tax rate increase, hours worked fall on impact and revert to their initial level before the shock. These patterns are broadly consistent with existing evidence. Second, similarly, the number of firms falls and reverts to its pre-shock level. However, differently from the response of hours worked, the response of the number of firms is hump shaped, with a trough occurring one year after the tax shock. Third, R&D and TFP fall, displaying pronounced hump-shaped responses, again consistent with the model.

1.1. *Identification of Tax Shocks and Estimation*

In this subsection, we discuss the identification of tax shocks and the estimation of the IRFs.

1.1.1. *Identification of tax shocks*

As in Barro and Redlick (2011), and most of the literature thereafter (see, e.g., Mertens and Ravn, 2013; Mertens and Montiel Olea, 2018 and Ferraro and Fiori, 2020), we consider a notion

[4] See Ramey (2016) for a review article of the empirical literature on the effects of tax changes.

of labour income that includes wages, self-employment, partnership and S-corporation income. We focus on average marginal tax rates (AMTRs), constructed as the sum of average marginal individual income tax rates (AMIITRs) and average marginal payroll tax rates (AMPTRs), using adjusted gross income shares as weights (see Seater, 1982; 1985 and Barro and Sahasakul, 1983; 1986 for a discussion).

The US federal income tax policy's post-WWII history includes significant changes in marginal tax rates (Romer and Romer, 2009). However, most of these changes result from policy actions to offset cyclical downturns. This pattern poses well-known challenges for identifying the causal effects of tax changes on macroeconomic variables. Therefore, we follow the narrative approach proposed by Romer and Romer (2010) to overcome these issues. In this approach, legislated changes in tax liabilities are classified as 'exogenous', based on the motivation for the legislative action being long-run considerations unrelated to the business cycle or inherited budget deficits and as 'endogenous' otherwise. Based on this classification, we calculate a time series of exogenous changes in AMTRs. As in Mertens and Montiel Olea (2018), we measure the impact of an exogenous tax change as the difference between two counterfactual tax rates. We calculate the first counterfactual tax rate using year $t-1$ income distribution and year t statutory tax rates and brackets; the second is calculated based on the year $t-1$ income distribution, and year $t-1$ tax rates and brackets. The difference between the two isolates the impact that a legislated tax change implemented in year t had on AMTR.[5]

Figure 1(a) shows the resulting time series of tax shocks and the observed changes in marginal tax rates for 1977–2012. Panel (b) shows the time series of the marginal tax rates for the same period. At least two patterns are worth stressing. First, as shown in panel (a), tax shocks are indeed associated with changes in marginal tax rates. Two notable examples are the negative tax shocks of the Tax Reform Act of 1986, and the Jobs and Growth Tax Relief Reconciliation Act of 2003. Second, as shown in panel (b), marginal tax rates have fallen from the early 1980s to the early 1990s. AMIITRs and AMTRs have fluctuated around 22% and 32%, respectively, since then.

1.1.2. *Estimation of IRFs*

We are interested in gauging the dynamic effects of tax shocks on six endogenous variables of interest, $Y \equiv [Hours, Firms, R\&D, TFP, G, AMTR]'$, where *Hours* is log per capita hours worked, *Firms* is log per capita number of firms, *R&D* is log per capita R&D investment, *TFP* is log utilisation-adjusted total factor productivity from Fernald (2014) and G is log per capita government purchases. To estimate the IRFs to a marginal tax rate shock, we rely on the local projection method of Jordà (2005) and IV regressions where we instrument changes in the *AMTR* with the tax shocks in Figure 1. Our sample of annual observations covers the period 1977–2012.[6]

We estimate the following regression separately for each horizon $h = 0, 1, 2, 3, 4$ up to four years after the tax shock:

$$Y_{i,t+h} = \alpha_h + \beta_{i,h}\Delta AMTR_t + \gamma_{i,h}(L)Y_{t-1} + \delta_{i,h}X_t + e_{i,t+h}.$$

[5] To account for potential 'anticipation effects', we include only individual income tax liability changes legislated and implemented within the year; this approach is in line with Mertens and Montiel Olea (2018). According to this criterion, we identify six tax changes as exogenous for 1977–2012: (1) Revenue Act of 1978; (2) Economic Recovery Tax Act 1981; (3) Tax Reform Act of 1986; (4) Omnibus Budget Reconciliation Act of 1990; (5) Omnibus Budget Reconciliation Act of 1993; (6) Jobs and Growth Tax Relief Reconciliation Act of 2003.

[6] Figure A.1 shows time series of the variables of interest. Data for the number of firms from the Business Dynamics Statistics (BDS) of the U.S. Census Bureau starts in 1977.

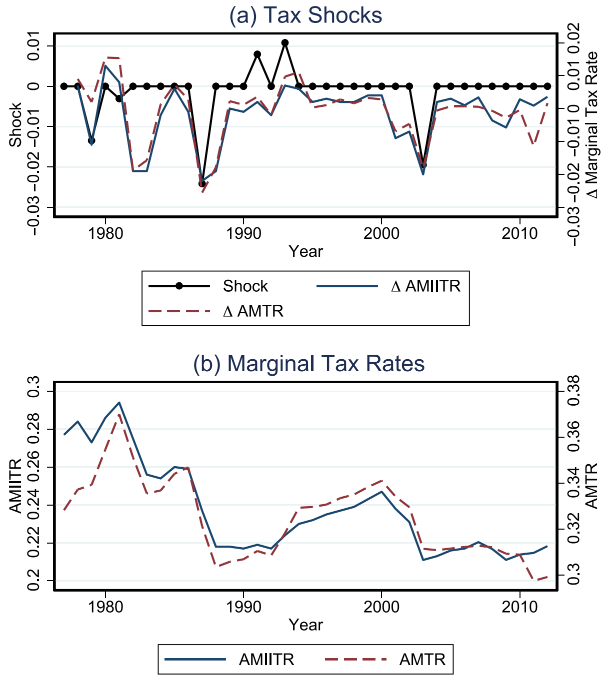

Fig. 1. *Tax Shocks and Marginal Tax Rates.*
Notes: Panel (a) shows the time series of constructed tax shocks as in Mertens and Montiel Olea (2018) and changes in AMIITRs and AMTRs for 1977–2012. Panel (b) shows AMIITRs and AMTRs for the same period.

Here Y_i is the variable of interest, $\Delta AMTR$ is the change in the $AMTR$, Y is the vector of endogenous variables specified above, X includes a trend and a quadratic trend, and $\gamma_{i,h}(L)$ is a polynomial in the lag operator. Regressions include two lags of endogenous variables. As in Ramey (2016), we calculate the response of Y_i at time $t+h$ to a tax shock at time t as $\beta_{i,h}$ times the coefficient on the tax shock in the first-stage regression.[7]

1.2. *Dynamic Responses to Tax Shocks*

Figure 2 shows the estimated IRFs for Jordà-IV regressions.[8] The marginal tax rate rises on impact by approximately 0.7 percentage points and returns to its initial level virtually four years after the shock. In response to this temporary, marginal tax rate increase, hours worked, the number of firms, R&D and TFP all drop below their levels before the shock and slowly go back after a few years. All variables but hours worked display hump-shaped responses.

Per capita hours worked fall on impact, stay virtually flat up to three years after the shock, and revert to their level before the shock by year four. The magnitude and shape of the response are broadly consistent with existing evidence (see, e.g., Barro and Redlick, 2011 and

[7] The first-stage regression is $\Delta AMTR_t = \alpha_0 + \beta_0 TaxShock_t + \gamma_0(L)Y_{t-1} + \delta_0 X_t + u_t$.

[8] IRFs based on the local projections of Jordà (2005) where tax shocks enter the regressions as right-hand side variables instead of as an instrument for changes in the AMTRs have similar shapes and magnitude, but larger confidence bands; see Figure A.2.

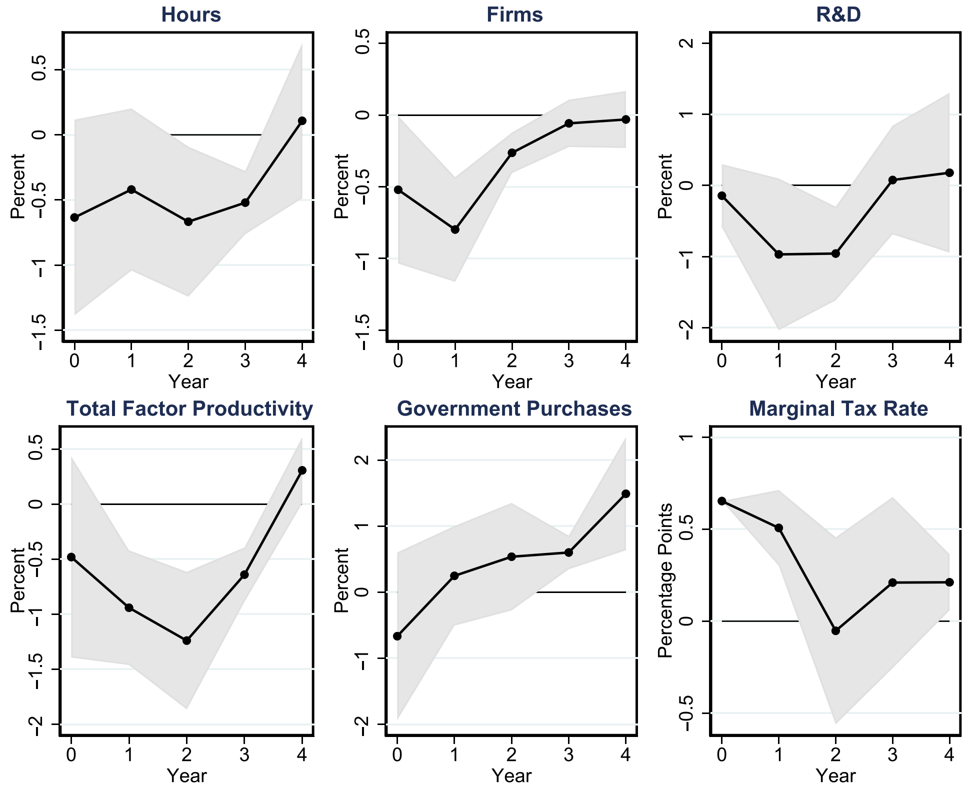

Fig. 2. *Empirical IRFs to a Marginal Tax Rate Increase.*
Notes: The figure shows the IRFs to a marginal tax rate shock. IRFs are estimated with the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the (heteroskedasticity and autocorrelation) HAC-robust residual covariance matrix of Newey and West (1994).

Mertens and Ravn, 2013). On impact, hours worked drop by approximately 0.63%. At the sample average for the AMTR of 0.325 for 1977–2012, the impact response in hours worked implies an elasticity of roughly $-0.63/(0.66/(1-0.325)) \approx -0.64$. This number is well in the ballpark of typical microeconomic estimates of labour supply elasticities (see Chetty *et al.*, 2012, Table 2).

The impulse responses of the number of firms, R&D and TFP are hump shaped. The number of firms falls on impact by about 0.5%, reaches a trough of −0.76% one year after the shock and reverts to its pre-shock level.[9] Four years after the shock, the number of firms has reverted to its level before the shock. In comparison, R&D falls by 1% two years after the shock and reverts to its pre-shock level. Finally, TFP reaches a trough of approximately −1.21% three years after the shock and reverts.

[9] Figure A.3 shows that the entry rate (the number of entrants divided by the number of firms) falls on impact and reverts to the level before the shock by year four. In contrast, the exit rate (the number of firm deaths divided by the number of firms) rises on impact, but by much less than the entry rate, and is virtually at its pre-shock level two years after the shock.

2. Model

We consider an economy without physical capital. More precisely, there is no capital in the neoclassical sense of a homogeneous, durable good accumulated through foregone consumption. Instead, there are differentiated, non-durable, intermediate goods. One can think of these goods as capital, albeit with a 100% instantaneous depreciation rate.[10] The relevant notion of capital embodied in the model is the stock of knowledge, a non-rival good that is partially excludable and privately produced by firms.

At the aggregate level, knowledge capital accumulates through the creation of new products by entrants (horizontal or expanding-variety innovation) and the improvements in the quality of existing products by incumbents (vertical innovation). The average level of quality and the mass of firms are the two aggregate state variables of this economy that determine the individual firms' incentives to enter and innovate. In our setting, firm entry and quality-improving investments are forward-looking decisions so that the entire time paths of tax rates and government spending impinge on equilibrium allocations.

2.1. *Household Sector*

Time is discrete and continues forever, indexed by $t = 0, 1, \ldots, \infty$. There is a representative household with a unit measure of infinitely lived members. Each member has an endowment of one unit of time per period. Household's preferences are described by

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j [\log(c_{t+j}) + \gamma \log(1 - l_{t+j})], \tag{1}$$

where $\mathbb{E}_t$ denotes the mathematical expectation conditional on time t information, c_t and l_t are consumption and the fraction of time spent at work, respectively, β is the time discount factor and γ parametrises the utility of leisure.

Each period, the household allocates its resources on consumption, c_t, purchases of bonds, b_{t+1}, and of equity shares issued by firms in the intermediate goods sector, $\int_0^{N_{t+1}} V_{i,t} s_{i,t+1} di$, where $V_{i,t}$ is the price per share and N_{t+1} is the mass of firms at the end of period t. The mass of firms evolves over time according to $N_{t+1} = (1-\delta)N_t + \Delta_t^N$, where δ is the exogenous and constant probability that a firm exits at the beginning of period (i.e., before production), and Δ_t^N is the mass of new firms entering the intermediate goods sector.[11] New firms that enter in period t and survive the exogenous death shock start operating and paying dividend in $t+1$. Thus, the mass of operating firms at period t is $\tilde{N}_t \equiv (1-\delta)N_t$. Household's resources consist of wages, $w_t l_t$, returns on bond holdings, $R_{t-1}^b b_t$, distributed dividends plus the ex-dividend value of initial share positions, $\int_0^{\tilde{N}_t} (D_{i,t} + V_{i,t}) s_{i,t} di$, where the $D_{i,t}$ are firm i's distributions per share, and lump-sum transfers, Ω_t. The household faces a proportional tax rate, τ_t, on labour income so that total tax liabilities are $\tau_t w_t l_t$. Hence, the household's flow budget constraint is

$$c_t + b_{t+1} + \int_0^{N_{t+1}} V_{i,t} s_{i,t+1} di = (1-\tau_t) w_t l_t + R_{t-1}^b b_t + \int_0^{\tilde{N}_t} (D_{i,t} + V_{i,t}) s_{i,t} di + \Omega_t. \tag{2}$$

[10] Notable examples of endogenous growth models that include capital accumulation and innovation are Romer (1990) and Howitt and Aghion (1998).

[11] Since we set population constant, a positive exit probability is required for the model to have symmetric dynamics in the neighbourhood of the deterministic steady state of the economy (Peretto, 1998; Peretto and Connolly, 2007).

The household takes the tax rate, τ_t, government transfers, Ω_t, prices, $(w_t, R^b_{t-1}, V_{i,t})$, and distributions, $D_{i,t}$, as given and chooses consumption, c_t, labour supply, l_t, bond holdings, b_{t+1}, and equity shares, $s_{i,t+1}$, given the bonds, b_t, and shares, $s_{i,t}$, held at the beginning of the period, to maximise lifetime utility (1) subject to the budget constraint (2).

The household's optimal plan satisfies an intratemporal condition for labour supply,

$$\gamma c_t = (1 - \tau_t) w_t (1 - l_t),$$

and two Euler equations for bond and asset holdings,

$$1 = \mathbb{E}_t [M_{t,t+1} R^b_t], \tag{3}$$

$$V_{i,t} = \mathbb{E}_t [(1 - \delta) M_{t,t+1} (D_{i,t+1} + V_{i,t+1})], \tag{4}$$

where $M_{t,t+1} \equiv \beta c_t / c_{t+1}$ is the stochastic discount factor (SDF).

2.2. *Production and Innovation*

The business sector produces a final, homogeneous consumption good and a continuum of intermediate goods differentiated by quality. We choose the final good as the numéraire, so its price is one. The final good has four uses: (*i*) private and public consumption; (*ii*) input into the production of intermediate goods; (*iii*) investment in quality improvements of existing intermediate goods; (*iv*) entry and creation of new intermediate goods.

2.2.1. *Final good*

The final good sector is competitive. There is a representative firm that uses intermediate goods, $\{X_{i,t}\}$, and labour, L_t, to produce the final good, Y_t. Intermediate goods differ by quality, $\{Z_{i,t}\}$. The production technology is

$$Y_t = \int_0^{\tilde{N}_t} X^{\theta}_{i,t} \left(Z^{\alpha}_{i,t} Z^{1-\alpha}_t \frac{L_t}{\tilde{N}^{\eta}_t} \right)^{1-\theta} di, \tag{5}$$

where $\tilde{N}_t = (1 - \delta) N_t$ is the mass of firms at the beginning of period t that corresponds to the mass of intermediate goods available for purchase. The parameter $\eta \leq 1$ captures labour's degree of congestion (or rivalry) across intermediate goods. For $\eta = 0$, there is no congestion, and the whole labour force can use every intermediate good with no productivity loss; a case of extreme economies of scope that manifest as strong social increasing returns to product variety in equilibrium. For $\eta = 1$, there is complete congestion; a case of no economies of scope and no social returns to variety.

The technology in (5) implies that the productivity of the labour input depends on each good i's quality, $Z_{i,t}$, and average quality of intermediate goods, $Z_t = (1/\tilde{N}_t) \int_0^{\tilde{N}_t} Z_{i,t} di$. This property is the defining feature of vertical innovation. Higher-quality intermediate goods perform similar functions to those performed by lower-quality ones; however, they increase the efficiency of the production process and, as a result, reduce unit production costs.

The final good producer takes the intermediate good i's quality, $Z_{i,t}$, and average quality, Z_t, as given. It maximises profits by setting the value marginal product of each intermediate good i equal to its price, $p_{i,t}$, and the value marginal product of labour equal to the wage, w_t. Perfect competition in the final good sector and the production technology in (5) imply zero profits. The final good producer's problem yields a demand for intermediate goods,

$$X_{i,t} = \left(\frac{\theta}{p_{i,t}}\right)^{1/(1-\theta)} Z_{i,t}^{\alpha} Z_t^{1-\alpha} \frac{L_t}{\tilde{N}_t^{\eta}}, \tag{6}$$

and a labour demand,

$$w_t L_t = (1-\theta) Y_t. \tag{7}$$

2.2.2. *Intermediate goods*

The intermediate goods sector is monopolistically competitive and consists of firms that produce differentiated intermediate goods. An incumbent operates a technology that requires one unit of the final good per units of the intermediate good produced, and the payment of a fixed operating cost, ϕZ_t. Firm i's gross cash flow (revenues minus production costs) is $F_{i,t} \equiv X_{i,t}(p_{i,t} - 1) - \phi Z_t$, where $X_{i,t}$ and $p_{i,t}$ are output and unit output prices, respectively. An incumbent can upgrade the quality of its intermediate good by investing $I_{i,t}$ units of final output; however, investment is subject to adjustment costs as in Christiano *et al.* (2005):

$$Z_{i,t+1} = Z_{i,t} + \left[1 - \frac{\psi}{2}\left(\frac{I_{i,t}}{I_{i,t-1}} - z\right)^2\right] I_{i,t}. \tag{8}$$

Here z is the economy's long-run growth rate (i.e., Z_t/Z_{t-1} on the balanced growth path) and ψ is a parameter that regulates the adjustment cost.[12]

The incumbent takes the demand curve for intermediate goods in (6), and the law of motion for quality (8) as given and chooses the output price, $p_{i,t}$, and investment, $I_{i,t}$, given the quality of its own intermediate good, $Z_{i,t}$, and average quality, Z_t, to maximise the cum-dividend value of the firm, $D_{i,t} + V_{i,t}$. Iterating forward the intertemporal condition for asset holdings (4), and applying the standard no-bubble condition on the terminal value of the firm, yields the ex-dividend value of the firm, $V_{i,t}$, as the expected present discounted value of dividends:

$$V_{i,t} = \mathbb{E}_t \sum_{j=1}^{\infty} \tilde{M}_{t,t+j} D_{i,t+j}$$

with $D_{i,t+j} = F_{i,t+j} - I_{i,t+j}$ the distributed dividends. The intermediate goods producer's problem yields a constant markup over the marginal cost pricing rule, $p_{i,t} = 1/\theta$, and an intertemporal condition for investment,

$$\mathbb{E}_t \tilde{M}_{t,t+1}\left[\left(\frac{1-\theta}{\theta}\right)\alpha \frac{X_{i,t+1}}{Z_{i,t+1}} + q_{i,t+1}\right] = q_{i,t},$$

where $q_{i,t}$ is the ratio of the Lagrange multiplier associated with (8) to the marginal utility of consumption and satisfies

$$\mathbb{E}_t\left[\tilde{M}_{t,t+1} q_{i,t+1} \psi \left(\frac{I_{i,t+1}}{I_{i,t}} - z\right)\left(\frac{I_{i,t+1}}{I_{i,t}}\right)^2\right]$$
$$= 1 - q_{i,t}\left[1 - \frac{\psi}{2}\left(\frac{I_{i,t}}{I_{i,t-1}} - z\right)^2 - \psi\left(\frac{I_{i,t}}{I_{i,t-1}} - z\right)\frac{I_{i,t}}{I_{i,t-1}}\right].$$

[12] The original deterministic model on which we build exhibits a monotonic response of firm-specific R&D to a permanent tax change. Adding the adjustment cost in (8) allows the model to produce a non-monotonic response to a tax shock independently of whether the shock is permanent or temporary, as in Figure 2.

Firms' entry in the intermediate goods sector requires νX_t units of final output, where $X_t = (1/\tilde{N}_t)\int_0^{\tilde{N}_t} X_{i,t}di$ is the average quantity of intermediate goods. The economy starts with a range of intermediate goods, each supplied by a firm. Because of the sunk entry cost, entrants do not find it profitable to supply an existing good in Bertrand's competition with the incumbent. They introduce instead a new intermediate good that expands product variety. Positive entry implies that the ex-dividend value of the firm equals the sunk entry cost, i.e., $V_{i,t} = \nu X_t$ for all $t \geq 0$. The mass of new firms that enter the intermediate goods sector in the current period starts operating and paying out dividends next period. Entrants finance entry by issuing equity, and they enter at the average quality level, Z_t. This simplifying assumption supports the symmetry of the equilibrium.

2.3. *Government*

The government purchases final goods and finances spending by levying distortionary taxes, and balances the budget period by period with lump-sum transfers. Therefore, in the model Ricardian equivalence holds. The government's budget constraint reads $G_t + \Omega_t = T_t$, where G_t is public consumption, Ω_t denotes lump-sum transfers and $T_t = \tau_t w_t l_t$ is tax revenues. As customary in the literature, government spending is modelled as a share of gross domestic product (GDP), so that $G_t = g_t \mathcal{Y}_t$ with $0 \leq g_t < 1$, where $\mathcal{Y}_t$ denotes GDP. Note that government purchases of final goods are a 'pure waste' and, thus, do not affect the marginal utility of private consumption or production. As is well known, this approach allows one to focus on the pure effects of distortionary income taxation.

2.4. *General Equilibrium*

We now turn to the general equilibrium of the model. Since the equilibrium is symmetric, we drop the i subscript so that, for example, $X_t \equiv X_{i,t}$ denotes both firm-level and average intermediate goods production. Market clearing in the labour and asset markets requires $l_t = L_t$ and $s_t = 1$, $b_t = 0$, respectively, whereas market clearing in the goods market yields the aggregate resource constraint, such that gross output is either consumed or invested in activities that generate future income and product,

$$C_t + G_t + \mathcal{I}_t + \mathcal{Q}_t = Y_t,$$

where C_t and G_t are private and public consumption, respectively, $\mathcal{I}_t$ indicates investment (i.e., business R&D expenditures and entry costs) and $\mathcal{Q}_t$ indicates intermediate expenses (i.e., intermediate inputs and fixed operating costs).[13]

2.4.1. *Determinants of the labour input*

We now discuss the intratemporal trade-offs that drive the determination of labour. In setting the labour supply, the household equates the marginal rate of substitution (MRS) between consumption and leisure to the wage. In addition, labour tax rates introduce a wedge between the MRS and the wage:

$$\gamma C_t = (1 - \tau_t) w_t (1 - L_t). \tag{9}$$

[13] See Appendix B for the full list of equilibrium conditions.

Equation (9) describes an upward-sloping labour supply curve. Note that in the baseline formulation of the model, tax revenues are only partially rebated back to the household as they finance government consumption.

To provide insight into the equilibrium labour response to tax changes, it is useful to combine household's labour supply (9) and labour demand of the final good producer (7):

$$\gamma \frac{L_t}{1-L_t} = (1-\tau_t)\frac{1-\theta}{C_t/Y_t}.$$

Changes in the labour tax rate directly impact the aggregate labour input through standard labour supply/demand forces, and an indirect equilibrium effect through the aggregate consumption-to-output ratio, C_t/Y_t. Moreover, the extent to which C_t/Y_t responds to τ_t depends on the business sector's response, which operates through changes in entrants' investment in firm creation (net firms' entry) and incumbents' investment.

2.4.2. *Determinants of long-run growth*

A system of two equations in two unknowns determines the per capita output growth rate along a balanced growth path (BGP) with constant tax rates. The two equations link the quality-adjusted firm size, $x_t \equiv X_t/Z_t$, to the steady-state gross growth rate of quality improvement, $z_t \equiv Z_t/Z_{t-1}$. Along such a BGP, z_t and x_t are constant. (Henceforth, we omit time subscripts unless needed for clarity.)

The first equation is the product innovation (PI) locus that captures the incentives for firms' entry:

$$z = 1 - \phi + \left[\frac{1-\theta}{\theta} - \frac{\nu(1-(1-\delta)\beta)}{(1-\delta)\beta}\right]x. \tag{10}$$

The second equation is the quality innovation (QI) locus that captures the incentives for the quality-improving investment of incumbents:

$$z = (1-\delta)\beta\left[\left(\frac{1-\theta}{\theta}\right)\alpha x + 1\right]. \tag{11}$$

The PI locus in (10) describes the steady-state quality-adjusted R&D investment rate, $I/Z = z - 1$, that equalises the rate of return to entry to the rate of return to quality-improving investment, given the value of x. The QI locus in (11) describes instead the steady-state investment rate that incumbents generate, given quality-adjusted firm size, x, that they expect to achieve in equilibrium. The steady state lies at the intersection of these two loci in the (x, z) space, as illustrated in Figure 3.

The existence and stability of the steady state require an intercept condition that the PI locus, starts below the QI locus and a slope condition that the PI locus is steeper than the QI locus. Together they imply that a stable, steady state (x^*, z^*) exists with the PI cutting the QI locus from below. To see the stability of such a steady state, note that if the system starts at a slightly higher $x > x^*$, then the return to product innovation is higher than the return to quality innovation (since the PI is above the QI locus to the immediate right of the intersection). This situation spurs entry and increases the mass of firms. Since x is inversely related to the mass of firms, x then falls, forcing the system to revert to steady-state value x^*.

In the model with constant population, the steady-state growth rate of quality, z^*, is the only driver of aggregate TFP and real GDP growth. This result is due to the presence of fixed operating

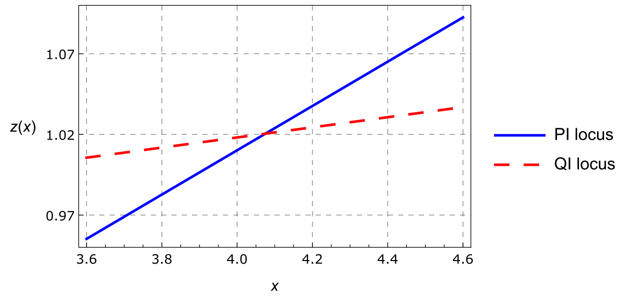

Fig. 3. *Steady-State Growth Rate of Quality Improvement.*
Notes: On the horizontal axis, $x_t \equiv X_t/Z_t$ is the quality-adjusted firm size, whereas on the vertical axis, $z_t \equiv Z_t/Z_{t-1}$ is the gross growth rate of quality improvement. The PI locus (solid line) describes the gross growth rate of quality improvement, z_t, needed to equalise the rate of return to entry to the rate of return to quality-improving investment, given the value of x_t. The QI locus (dashed line) describes the gross growth rate of quality improvement, z_t, that incumbents generate, given the quality-adjusted firm size, x_t, that they expect to achieve in equilibrium.

costs. An ever-expanding mass of products puts pressure on the economy's aggregate resources by duplicating fixed costs, making firms' entry, and so expanding-variety innovation, irrelevant for long-run productivity growth.

In symmetric equilibrium, the production technology for the final good (5) gives TFP as a function of the mass of firms at the beginning of the period, $\tilde{N}_t$, and average product quality, Z_t:

$$TFP_t = \tilde{N}_t^{1-\eta} Z_t. \tag{12}$$

For the case of no labour congestion ($\eta = 0$), TFP is linear in the mass of firms and quality. For the case of complete labour congestion ($\eta = 1$) instead, TFP is independent of the mass of firms and equals Z_t. Given (12), the TFP growth rate is

$$\Delta \log TFP_t = (1-\eta)\Delta \log \tilde{N}_t + \Delta \log Z_t.$$

In the steady state of the model, the growth rate of $\tilde{N}_t$ is proportional to the population growth rate. This steady-state property is the semi-endogenous growth component of the model, which we shut down here by assuming constant population.[14] Hence, in the long run, TFP growth equals quality growth, $\Delta \log TFP_t = \Delta \log Z_t$, and labour tax changes have no growth effects, whether permanent or transitory. In steady state, the constant growth rate of quality depends only on quality-adjusted investment, I_t/Z_t, which in turn depends on quality-adjusted firm size, $x_t \equiv X_t/Z_t = \theta^{2/(1-\theta)} L_t/\tilde{N}_t^{\eta}$. Any labour tax change that affects the long-run level of the labour input mandates an adjustment in the long-run mass of firms that leaves x unchanged.

In the short run, however, labour tax changes impact TFP growth via changes in quality growth and changes in the mass of firms. The dynamics can be described by a parsimonious state-space representation that involves quality-adjusted firm size, x_t, as the endogenous state variable, and the tax rate, τ_t, as the exogenous driving force.

[14] Allowing for positive population growth does not change results in any substantive way.

2.4.3. *The propagation mechanism of labour tax changes*

We now describe the propagation mechanism of tax changes embedded in the model. As evident from (10)–(11), the labour tax rate does not determine the steady-state growth rate of quality improvement. In other words, in the long run, tax rate changes have no long-term effects on aggregate productivity growth. In this sense, labour taxes have level effects, but no growth effects. The mechanism that delivers this result is the exact mechanism responsible for the absence of a scale effect. In the model, the long-run growth rate does not depend on the population level or the labour input.

The PI locus in (10) and QI locus in (11) capture the insight that firms' entry and R&D investment decisions by incumbents do not directly respond to changes in labour taxes, but only indirectly through changes in quality-adjusted firm size. A *permanent* change in the tax rate affects the equilibrium labour input and aggregate demand for intermediate goods, expanding the market in which firms operate. While this market-size effect is present in transition dynamics, it vanishes in the long run with the entry/exit of firms. To see this, (1) fix the mass of firms, then a change in the tax rate affects the quality-adjusted firm size, thereby incentivising quality-improving innovation. Everything else equal, this would have steady-state growth effects. (2) Now, let the mass of firms vary as in the free-entry equilibrium: the profitability of incumbents changes, and the mass of firms endogenously adjusts (via net entry) to bring the economy back to the initial steady-state level of firm size. As a result, the adjustment process through firms' entry sterilises the long-run growth effect of the initial tax change.

In the short run, however, the economy exhibits a positive co-movement between the labour input used in production, which in general equilibrium equals hours worked, and the mass of firms. To the extent that quality-adjusted firm size falls, R&D falls, generating a slowdown in productivity. Such a slowdown is temporary as the economy converges to the new steady-state with the same long-run growth rate before the change in the tax rate.

If the tax rate change is *transitory*, then agents form expectations about the future path of tax rates. For example, consider the case where the tax rate drops first and then returns to its previous level after some periods. In anticipation of these tax changes, households work more at the time of a lower tax rate and less when the tax rate reverts to its initial level. This adjustment in hours is the standard mechanism of intertemporal substitution of leisure. As a result, market size temporarily rises, leading to more entry and higher investment. This adjustment process ends when the economy settles on the new balanced growth path. While the model is amenable to studying permanent tax rate changes, here, we focus on temporary tax changes based on the narrative account of the US tax policy of Romer and Romer (2009; 2010). Legislated tax changes are often permanent; however, governments typically partly or wholly overturn them over time.

3. Taking the Model to the Data

In this section, we parametrise the model. We begin with a brief narrative of post-war US fiscal policy; we then map the model to the national income and product accounts (NIPA). Finally, we turn to estimate model parameters related to preferences and technology.

3.1. *Post-War Fiscal Policy in the United States*

In the post-war period, the United States have experienced frequent changes in federal tax policy (see Romer and Romer, 2009; 2010 for a narrative account). Some of these changes were legislated

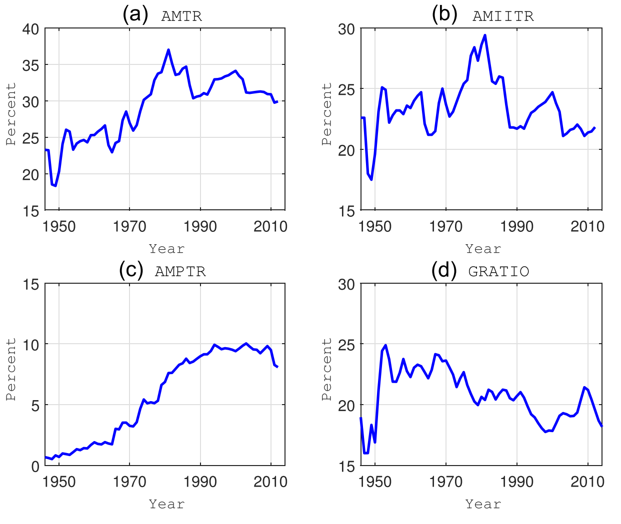

Fig. 4. *Post-War Fiscal Policy in the United States.*
Notes: Panel (a) shows the AMTR, which equals the AMIITR, as shown in panel (a), plus the AMPTR, as shown in panel (c). Panel (d) shows government purchases as a share of GDP (GRATIO).

as temporary, mainly motivated by the current state of the business cycle. Other changes were part of major tax reforms, e.g., the TRA of 1986. By contrast, government purchases as a share of GDP have been fairly stable since the Korean War of 1950–3. Here we describe the time-series behaviour of individual income tax rates and government purchases-to-GDP ratios that we later use as model inputs in our quantitative experiments.

3.1.1. *Individual income tax*

We view AMTR, as constructed by Barro and Redlick (2011), as a measure of the overall distortion to labour supply.[15] Panels (a)–(c) of Figure 4 show the time series of AMTR and its components.

A few remarks are in order. First, the time-series average of AMTR is 29%, with an average AMIITR of 23% and an average AMPTR of 6%. Second, AMTR displays a marked upward trend from the early 1960s to the early 1980s. It fluctuates in the 24%–27% range over roughly 10 years from 1960 to 1970. In the 1970s, AMTR sharply rises from 25% to the post-war peak of 38% in the early 1980s. This acceleration was primarily due to the bracket creep effects of the rising inflation during the Great Inflation of the 1970s. After the 1980s, reductions in the federal individual income tax rates, which have remained in the 20%–25% range since then, have almost entirely offset the sustained rises in the Federal Insurance Contributions Act tax. In addition to these long-run trends, the time series of AMTR features substantial year-to-year variation. As discussed in Mertens and Montiel Olea (2018), statutory changes in federal individual income taxes account for the bulk of the year-to-year variation in AMTRs. Consistently to the literature, AMTR does not include state-level taxes. However, the amount of short-run variation in state-level marginal tax rates is small (see Barro and Redlick, 2011).

[15] AMTR is the sum of AMIITR and AMPTR. The construction of AMTR uses a notion of labour income that includes wages, self-employment, partnership and S-corporation income.

3.1.2. *Government spending*

In addition to time-varying tax rates, the private sector also faces government purchases that vary over time. The government-spending-to-GDP ratio (GRATIO) in the model, g_t, is measured as GRATIO = GOV/GDP. GOV is government consumption expenditures, and gross investment, which includes federal (national defence plus non-defence), state and local government levels (NIPA Table 1.1.5, line 22), and GDP is gross domestic product (NIPA Table 1.1.5, line 1). The source of the data is NIPA. In the model, GRATIO equals 20.8%, which is the average in the data for 1946–2014.

Figure 4(d) shows the time series for GRATIO. For the post-war period, the mean GRATIO is roughly 21%. The GRATIO was below 20% until 1950. Then, it sharply rose from 17% in 1950 to the post-war peak of nearly 25% in 1953. Such a surge in government spending results from the increase in national defence expenditure due to the Korean War of 1950–3. To meet the financing needs for defence expenditure, the Revenue Act of 1950 raised the statutory top corporate income tax rate from 38% to 42% in 1950 and 52% in 1952. Since the mid-1950s, government spending has slowly declined to 18% of GDP in 2014.

3.2. *Mapping the Model to NIPA*

The model counterpart of the US NIPA implies the following split of gross output between GDP and intermediate expenses:

$$\underbrace{\underbrace{C_t + G_t}_{\substack{\text{private + public}\\ \text{consumption}}} + \underbrace{\tilde{N}_t I_t}_{\substack{\text{product quality}\\ \text{investment (R\&D)}}} + \underbrace{\nu X_t \Delta_t^N}_{\substack{\text{firm creation}\\ \text{investment}}}}_{\text{GDP}} + \underbrace{\underbrace{\tilde{N}_t X_t}_{\substack{\text{input}\\ \text{costs}}} + \underbrace{\phi \tilde{N}_t Z_t}_{\substack{\text{operating}\\ \text{costs}}}}_{\text{intermediate expenses}} = \underbrace{Y_t}_{\substack{\text{gross}\\ \text{output}}}.$$

We include R&D expenditures in the calculation of GDP. This approach is consistent with the NIPA approach. Since the 2013 NIPA release, BEA has recognised expenditures by business, government and non-profit institutions on R&D as an investment in fixed assets. In the previous NIPA approach, R&D business expenses—whether purchased from others or carried out in-house—were treated as intermediate expenses used up during the production of other goods and services rather than as capital expenses that generate future income.[16]

3.3. *Parametrisation*

We are to assign values to nine parameters describing preferences and technology. A model period is a year. As is well known, in dynamic general equilibrium models, parameters do not typically have a one-to-one relationship to a specific moment. Nevertheless, the cross-equation restrictions implied by the theory highlight key relationships between model parameters and data moments. Here, we use these theoretical restrictions to inform our choice of the data moments used for estimation. Table 1 reports the parameter values.

[16] See Appendix B for further details on the calculation of GDP in the model related to the US national accounts.

Table 1. *Model Parameters.*

Parameter	Description	Value
Panel A. Preferences		
β	Time discount factor	0.981
γ	Utility of leisure	1.844
Panel B. Technology		
δ	Firm exit probability	0.090
θ	Elasticity of substitution of intermediate goods	0.870
ϕ	Fixed operating cost	0.539
α	Knowledge spillovers	0.235
ν	Sunk entry cost	0.101
η	Labour congestion	0.365
ψ	R&D adjustment cost	10.545

3.3.1. *Calibrated parameters*

Overall, we calibrate seven parameters $(\beta, \gamma, \delta, \theta, \phi, \alpha, \nu)$ to match seven moments in the US data: average growth rate of real GDP per capita (2%); firm's death rate (9%); real interest rate (4%); time spent working (0.33); average markup (15%); average profits-to-GDP ratio (9%); average R&D-to-GDP ratio (2.6%).

First, the time discount factor, β, is directly identified by the bond pricing equation (3), which along the BGP reduces to $\beta R^b/z = 1$, where z is the economy's steady-state growth rate. Given $z = 1.02$ and $R^b = 1.04$, $\beta = 1.02/1.04 = 0.981$. We set the value of the parameter for the utility of leisure, γ, so that the model matches the share of available time spent working 1/3.

Second, two parameters (δ, θ) are directly pinned down by targeted moments. In the model, δ is the exogenous and constant probability that a firm exits, which we map to the average firm's death rate from the Census BDS data of 9%. The elasticity of substitution of intermediate goods, θ, is directly related to the markup. In the model, firms in the intermediate goods sector have a unitary marginal cost and charge a unit output price of $1/\theta$. Targeting a value for the markup of 15%, roughly the average of estimated markups in Traina (2018), gives a value for θ of 0.87.[17]

Third, we jointly identify three parameters (ϕ, α, ν) using three equations: the model expressions for the economy's long-run growth rate, the R&D-to-GDP ratio and the profits-to-GDP ratio. In Appendix C we show that these three moments once expressed as functions of (ϕ, α, ν) have a unique solution that gives us each parameter as a function of the moments, given previously identified parameters.[18]

3.3.2. *Matching IRFs*

It remains to estimate the parameters η and ψ. To do so, we cannot use BGP relationships as ψ drops out of the steady-state equations altogether, and η only affects the steady state through the level of quality-adjusted firm size, x^*. As x^* is a latent variable we cannot read from the data, we follow a different strategy. Specifically, we pin down η and ψ by matching the empirical IRFs shown in Figure 2. We proceed in two steps.

[17] See De Ridder *et al.* (2022) and the references therein for an overview of markup estimates.

[18] Table C.1 in Appendix C provides a sensitivity analysis on how 1%, 5% and 10% changes in α affect the model-implied long-run growth rate, the R&D-to-GDP ratio and the profits-to-GDP ratio.

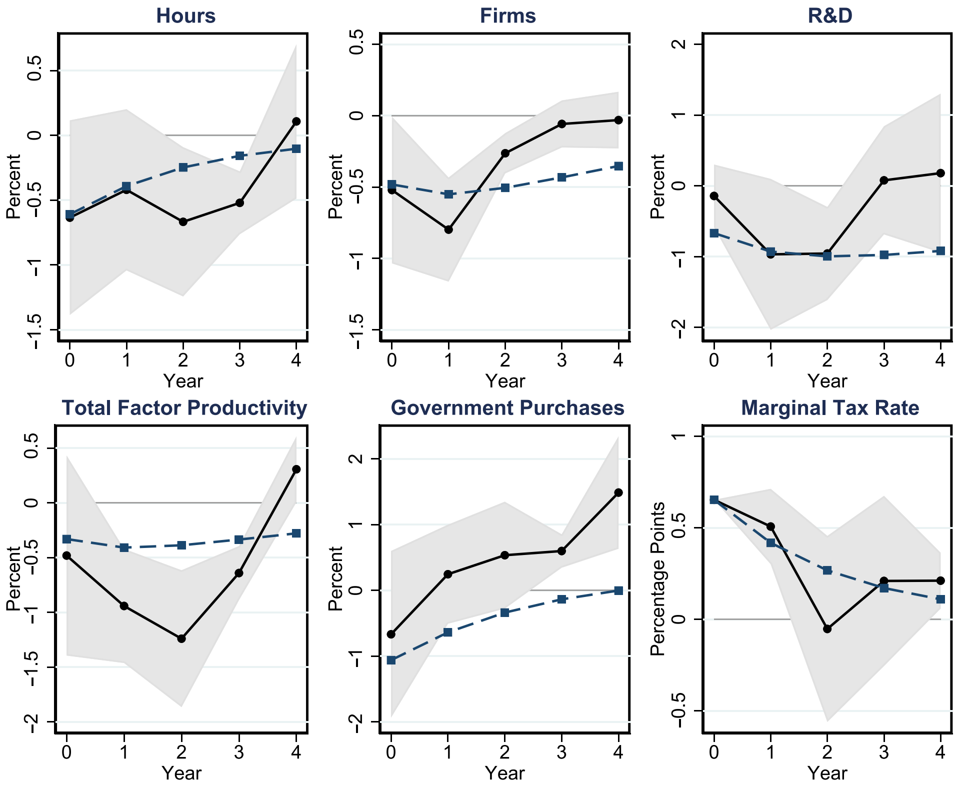

Fig. 5. *IRFs to a Marginal Tax Rate Increase—Model versus Data.*
Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2 and the IRFs to an equally sized increase in the labour tax rate in the model (dashed lines with squares). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

First, we assume an AR(1) process for the labour tax rate in the model and pick the SD of the innovation to the tax rate and the autoregressive parameter, so that the IRF of the labour tax rate in the model approximates well the empirical IRF of the marginal tax rate in the data. This approach guarantees that the agents in the model have realistic expectations about the magnitude and persistence of tax shocks.

Second, given the stochastic process for the tax rate, we pin down η and ψ for the model to match the empirical IRFs for the number of firms and R&D at period 1.5 (i.e., the midpoint of periods 1 and 2). This strategy has the advantage of accounting for the troughs of the number of firms and R&D, almost perfectly, matching the impact responses of hours and the number of firms. This procedure gives a value for η of 0.365 and a value of 10.545 for ψ. Figure 5 shows the model's IRFs versus the empirical ones from Figure 2.[19]

[19] We use Dynare (Adjemian *et al.*, 2011) to find a numerical solution of the model by relying on a second-order approximation to the solution around the deterministic steady state.

Overall, the model reproduces the main features of the empirical IRFs. In the model, as in the data, hours drop on impact and revert to their level before the shock. Also, the model successfully reproduces the hump-shaped responses of the number of firms, R&D and TFP. However, the model generally produces more persistence than our estimates. For instance, in the model, the mass of firms remains below the pre-shock level four years after the shock. In contrast, in the data, the number of firms has virtually returned to its level before the shock.[20]

4. Quantitative Predictions for the US Economy

Figure 5 shows that the model can successfully account for the salient properties of the propagation mechanism of labour tax changes in US data. In this section, we further examine the implications of US tax policy and use the model to quantify the economy's dynamic response to large, observed changes in marginal tax rates. We carry out two quantitative experiments.

In the first experiment, we feed to the model the observed AMTRs for 1977–2012, and quantify how much of the observed variation in aggregate data is due to variation in labour income taxes alone. Several laws legislated large changes in individual income tax rates over this period. For example, the Revenue Act of 1978; the Economic Recovery Tax Act (ERTA) of 1981 and the TRA of 1986, commonly referred to as the 'Reagan tax cuts'; the Omnibus Budget Reconciliation Act (OBRA) of 1990; the OBRA of 1993; the Jobs and Growth Tax Relief Reconciliation Act (JGTRRA) of 2003. Besides OBRA-90 and OBRA-93, all these tax changes were reductions in individual income taxes. We find that changes in marginal tax rates alone account for a sizeable share of the overall time-series variation in hours worked, number of firms, R&D and TFP.

In the second experiment, we use the model to evaluate the TCJA of 2017. While the TCJA comprises provisions on several aspects of the US tax code, here we focus on those pertaining to the individual income tax. The model predicts that a temporary, three percentage point cut in the marginal tax rate, set to expire in 2025 as in TCJA, leads to a gradual, sustained productivity growth acceleration. This temporary growth acceleration translates into a permanent gain in real GDP per capita of about 2% relative to a counterfactual economy without TCJA.

4.1. *Labour Tax Rates and Aggregate Volatility*

We feed to the model the marginal tax rates for 1977–2012, and compute equilibrium paths under perfect foresight that we compare with the US time series for the same period. We assume that the model economy was in the steady state in 1977, and that in 2012 the agents expect the labour tax rate to be at its 2012 value forever. Table 2 reports the SDs of the growth rates of hours worked, number of firms, R&D and TFP based on data for 1977–2012, and those calculated based on artificial data from three counterfactual economies.[21]

In the first counterfactual ($\mathcal{C}.1$), the labour tax rate is allowed to vary as in the data, keeping the government-spending-to-GDP ratio fixed at the 1977 value. Overall, changes in tax rates account for a noticeable share of the total observed variation in hours, number of firms, R&D and TFP. For example, the model generates one-third ($0.65\%/1.96\% \approx 33\%$) of the volatility of percent

[20] Figures C.1–C.8 in Appendix C show IRFs when we change the parameters η and ψ by 10% and 20%.

[21] All counterfactuals assume lump-sum transfers to balance the government budget on a period-by-period basis. This operational assumption is widely used, and allows one to examine the effects of tax changes without taking a stand on when and how the government will balance the intertemporal budget constraint. However, whether this assumption is empirically plausible is still open to debate (see, e.g., Seater, 1993). Ferraro and Peretto (2020) studied the implications of government debt without lump-sum transfers in this class of models.

Table 2. *Labour Tax Rates and Aggregate Volatility.*

	Data	$\mathcal{C}.1$ ($\Delta\tau$ only)	$\mathcal{C}.2$ (Δg only)	$\mathcal{C}.3$ ($\Delta\tau$ & Δg)
SD($\Delta Hours$)	1.96%	0.65%	0.30%	0.75%
SD($\Delta Firms$)	1.42%	0.72%	0.64%	1.03%
SD($\Delta R\&D$)	3.12%	1.39%	0.77%	1.67%
SD(ΔTFP)	1.36%	0.44%	0.40%	0.64%

Notes: The table shows SDs of the growth rates of hours worked, number of firms, R&D and TFP based on data for 1977–2012, and those calculated based on artificial data from the model under three counterfactual scenarios. $\mathcal{C}.1$ refers to the counterfactual where the labour tax rate is allowed to vary, keeping the government-spending-to-GDP ratio fixed at the 1977 value. $\mathcal{C}.2$ refers to the counterfactual where the government-spending-to-GDP ratio varies as in the data, keeping the labour tax rate fixed at the 1977 value. Finally, $\mathcal{C}.3$ refers to the counterfactual where both the tax rate and government-spending-to-GDP ratios vary as in the data.

changes in per capita hours worked and nearly half ($0.72\%/1.42\% \approx 51\%$) of the volatility in the growth rate of the number of firms. Similarly, changes in tax rates account for about one-third ($0.44\%/1.36\% \approx 32\%$) of the volatility in utilisation-adjusted TFP growth rates. In the second counterfactual ($\mathcal{C}.2$), the government-spending-to-GDP ratio is allowed to vary as in the data, while we keep the tax rate fixed at the 1977 value. Changes in government spending as those in the data account for a much smaller share of the variation in the variables of interest. Finally, in the third counterfactual ($\mathcal{C}.3$), tax rates and government spending vary as in the data. Overall, the model accounts for an even larger share of the variation in the data compared to counterfactuals one and two. Yet, a non-trivial percentage of this variation remains unexplained. This result is not surprising, as the model misses several important sources of cyclical fluctuations, such as oil price shocks and other business cycle shocks.

4.2. *The Tax Cuts and Jobs Act of 2017*

Available estimates point to a significant change in work incentives from TCJA. Mertens (2018) calculated that TCJA has reduced AMTR by 2.75 percentage points. According to the Tax Policy Center calculations, TCJA would reduce AMTRs on wages and salaries by 3.2 percentage points. Historically, the magnitude of these tax rate cuts is comparable to those previously legislated under the Revenue Act of 1964 and Tax Reform Act of 1986. Importantly, under TCJA, changes in individual income tax rates have been legislated as temporary and set to expire in 2025.

We proceed in two steps. First, we assume that the economy is on the BGP in 2017, with the following fiscal policy: $\tau_{2017} = 26\%$, and $g_{2017} = 20\%$. Second, in 2017, the new future path of tax rates was announced so that the private sector has perfect foresight about the announced path. We consider a three percentage point cut in the labour tax rate, which is the mid-point of the available estimates. Furthermore, the private sector anticipates that in 2025 the tax rate cut will expire. In that event, the tax rate returns to its 2017 value. So the path of tax rates under TCJA is $\tau_t = 23\%$ for $2018 \leq t \leq 2025$ and $\tau_t = 26\%$ for all $t \geq 2026$.

Figure 6 shows equilibrium paths from the model. In response to the temporary tax rate cut, the economy experiences a productivity growth acceleration, which leads to a permanent gain in per capita GDP relative to the BGP before the tax rate cut. As a result, the model predicts per capita GDP to be nearly 2% higher than the level that would have prevailed without TCJA by 2025.

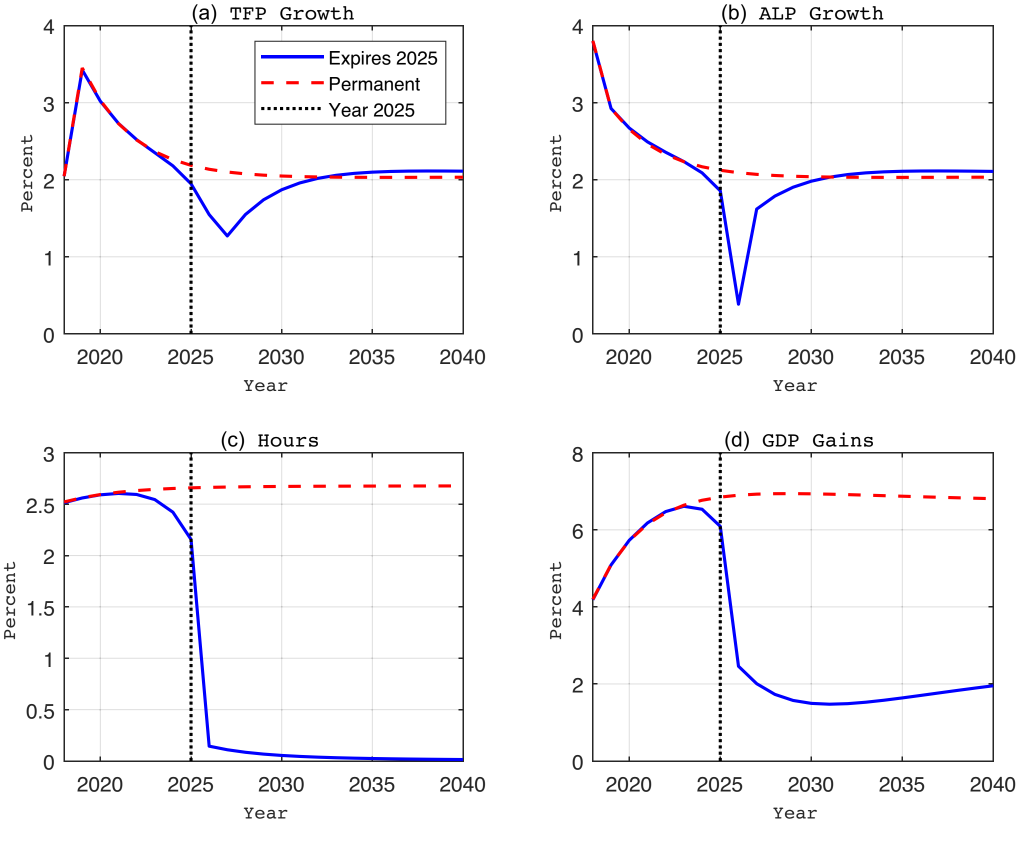

Fig. 6. *Model Predictions for the Tax Cuts and Jobs Act of 2017.*
Notes: Solid lines show equilibrium paths simulated from the model after a temporary, three percentage point tax cut set to expire in the year 2025, as in the TCJA of 2017. The model economy is assumed to be on the BGP in 2017 with a labour tax rate of 26%. The tax rate is 23% from 2018 to 2025 and returns to 26% from 2026 onwards. Dashed lines show paths under a permanent three percentage point tax cut, where we feed to the model a tax rate of 23% from 2018 onwards. In all panels, the government-purchases-to-GDP ratio remains constant at its 2017 level. Lump-sum transfers adjust to balance the government budget on a period-by-period basis.

A natural question is how and to what extent the temporary nature of the legislated tax changes matters for the current response of the economy to the announced tax rate cut. To address this question, we feed to the model an equally sized, permanent tax rate cut. Again, the model economy goes through a prolonged period of increased productivity growth, leading to about 7% permanent increase in per capita GDP by 2025. Under a permanent tax rate cut, the variability of growth rates is much reduced compared to the experiment featuring a temporary tax rate cut, pointing to the importance of intertemporal substitution.

5. Conclusion

We develop, estimate and provide empirical validation for a quantitative Schumpeterian growth model. A prominent feature of the theory is the equilibrium interaction between product and quality innovation: entrants create new products, whereas incumbents improve their existing products. The model is estimated to match salient moments of US data and accounts for the dynamic response of TFP, R&D, market hours worked and the number of firms per capita to narratively identified marginal tax rate shocks.

We use the model to evaluate the provisions of the TCJA of 2017 that pertain to the individual income tax. We find that a three percentage point cut in the average marginal personal income tax rate, set to expire in 2025 as in TCJA, raises real GDP per capita by 2% in 2025.

Overall, our results single out endogenous productivity growth as a quantitatively important channel for the propagation mechanism of temporary changes in labour taxes. Moreover, innovative investments greatly magnify labour supply responses to tax rate changes. Arguably, the far-reaching implication of our work is that market structure, through general-equilibrium forces, is a critical element in the quantitative evaluation of the short- and long-run effects of labour taxation.

Appendix A. Data and Additional Empirical Results

We use several datasets in our analyses. All the raw data files, together with the details on construction of variables, can be found in our replication package. Below, we briefly mention the name of each dataset, the file containing that data in the replication package, and its citation. All the following data are publicly available.

(1) 'Marginal Tax Rates'; `data_mmo.xlsx`; Mertens and Montiel Olea (2018).
(2) 'Business Dynamic Statistics'; `bds_f_all_release.xlsx`; BDS (2016).
(3) 'U.S. Population'; `CNP16OV.xls`; BLS (2017).
(4) 'U.S. Hours'; `B4701C0A222NBEA.csv`; BEA (2017).
(5) 'U.S. Total Factor Productivity'; `quarterly_tfp.xlsx`; Fernald (2014).
(6) NIPA Table 1.1.5; `NIPA_Tab10105A.xlsx`; BEA (2020).
(7) NIPA Table 1.5.3; `NIPA_Tab10503A.xlsx`; BEA (2020).

Appendix B. Model Derivations

B.1. Equilibrium Conditions

Here we list the model equations that we use to compute the model's equilibrium:

$$C_t + G_t + \tilde{N}_t I_t + \nu X_t(N_{t+1} - \tilde{N}_t) + \tilde{N}_t X_t + \phi \tilde{N}_t Z_t = Y_t, \tag{B.1}$$

$$Y_t = \theta^{2\theta/(1-\theta)} \tilde{N}_t^{1-\eta} Z_t L_t, \tag{B.2}$$

$$\gamma C_t = (1-\tau_t) w_t (1 - L_t), \tag{B.3}$$

$$V_t = \mathbb{E}_t[\beta(1-\delta)\tfrac{C_t}{C_{t+1}}(D_{t+1} + V_{t+1})], \tag{B.4}$$

$$w_t = (1-\theta)\theta^{2\theta/(1-\theta)} \tilde{N}_t^{1-\eta} Z_t, \tag{B.5}$$

$$X_t = \theta^{2/(1-\theta)} Z_t (L_t/\tilde{N}_t^{\eta}), \tag{B.6}$$

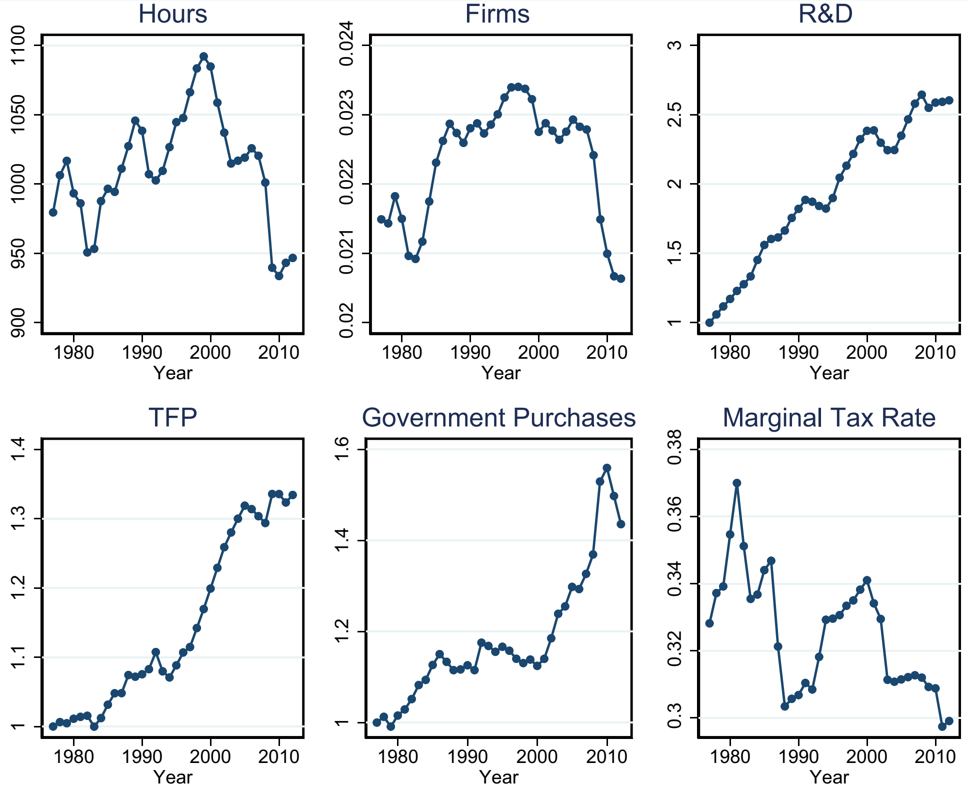

Fig. A.1. *Time Series of the Variables of Interest.*
Notes: The figure shows the time series of hours per capita (Hours), number of firms per capita (Firms), real R&D per capita (R&D), utilisation-adjusted TFP, real government purchases per capita and the average marginal tax rate (AMTR), for 1977–2012. We normalised R&D, TFP and government purchases to 1 in 1977.

$$Z_{t+1} = Z_t + I_t, \tag{B.7}$$

$$V_t = \nu X_t, \tag{B.8}$$

$$q_t = \mathbb{E}_t\left\{\beta(1-\delta)\frac{C_t}{C_{t+1}}\left[\left(\frac{1-\theta}{\theta}\right)\frac{\alpha X_{t+1}}{Z_{t+1}} + q_{t+1}\right]\right\}, \tag{B.9}$$

$$q_t\left(1-\frac{\psi}{2}\left(\frac{I_t}{I_{t-1}}-z\right)^2-\psi\left(\frac{I_t}{I_{t-1}}-z\right)\frac{I_t}{I_{t-1}}\right)+\mathbb{E}_t\left\{\beta(1-\delta)\frac{C_t}{C_{t+1}}q_{t+1}\psi\left(\frac{I_{t+1}}{I_t}-z\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right\}=1, \tag{B.10}$$

$$F_t = \left(\frac{1-\theta}{\theta}\right)\theta^{2/(1-\theta)}\left(\frac{L_t}{\tilde{N}_t^{\eta}}\right)Z_t - \phi Z_t, \tag{B.11}$$

$$D_t = F_t - I_t, \tag{B.12}$$

$$G_t + \Omega_t = T_t, \tag{B.13}$$

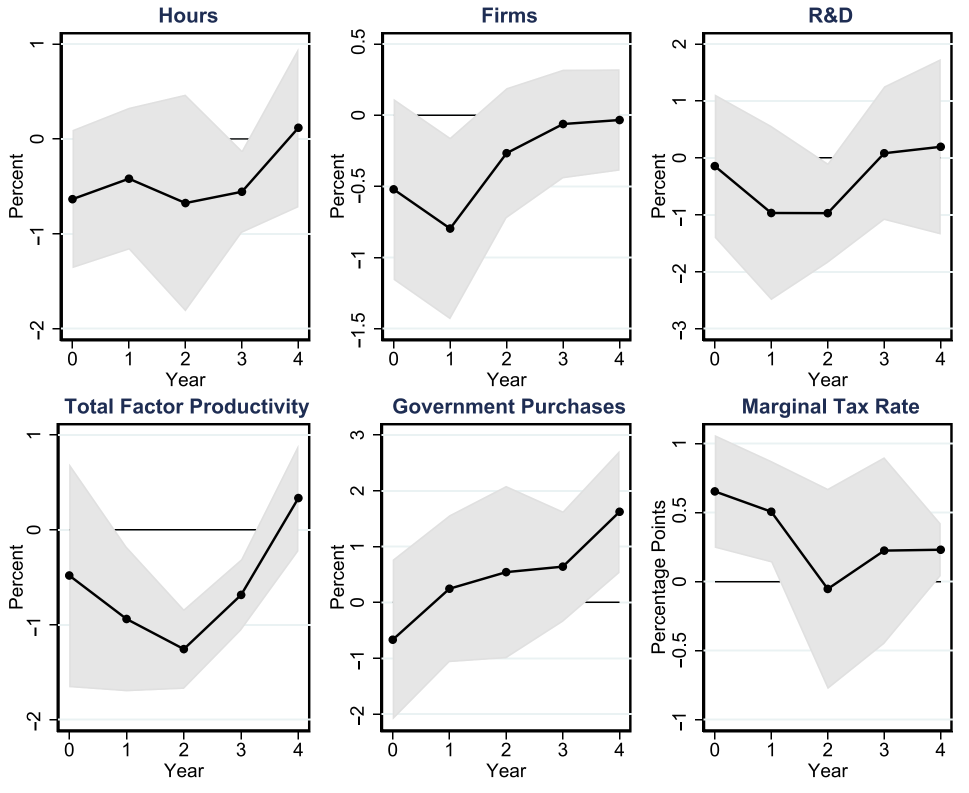

Fig. A.2. *Empirical IRFs to a Tax Rate Increase—Alternative Specification.*
Notes: The figure shows the IRFs to a marginal tax rate shock. IRFs are estimated with the local projection method of Jordà (2005). Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994). We estimate the following regression separately for $h = 0, 1, 2, 3, 4$ up to four years after the tax shock:

$Y_{i,t+h} = \alpha_h + \beta_{i,h} TaxShock_t + \gamma_{i,h}(L)Y_{t-1} + \delta_{i,h} X_t + \epsilon_{i,t+h}$ with $\beta_{i,h}$ the IRF of Y_i at horizon h.

$$G_t = g(Y_t - \tilde{N}_t X_t - \phi \tilde{N}_t Z_t), \tag{B.14}$$

$$T_t = \tau_t w_t L_t. \tag{B.15}$$

The above set of 15 equations with 15 variables fully describe the model.

B.2. Rate of Return to Equity and R&D Investment Schedules

Here we provide details on the derivation of the rate of return to incumbents' investment (RRI) and the rate of return to entrants' investment (RRE), or analogously to firm creation investment. We interpret RRI and RRE as investment schedules, represented in (i_t, r^a_{t+1}) space, where $i_t \equiv I_t/Z_t$

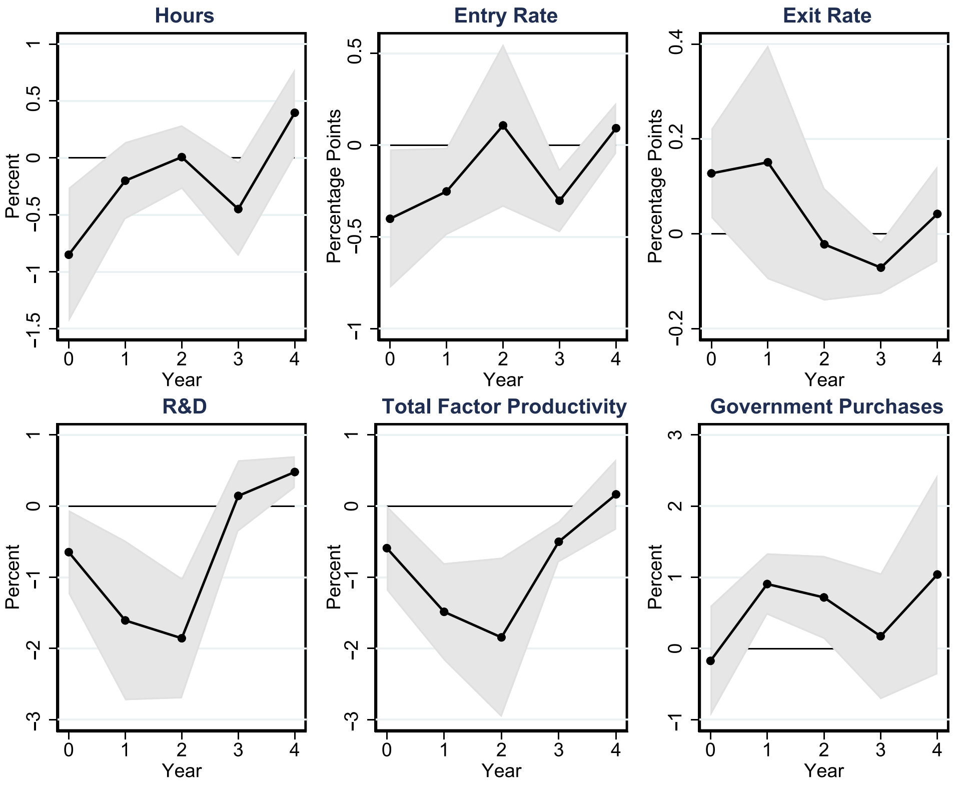

Fig. A.3. *Empirical IRFs of Firm Entry and Exit to a Tax Rate Increase.*
Notes: The figure shows the IRFs to a marginal tax rate shock. IRFs are estimated with the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994). Entry and exit rates are the numbers of entrants and firm deaths divided by the number of firms. Data are from BDS of the U.S. Census Bureau.

is the current R&D investment rate and r^a_{t+1} is the rate of return to corporate equity one period ahead.

The first-order condition for R&D investment (B.9) implies that $[(1-\theta)/\theta]\alpha X_{t+1}/Z_{t+1} + 1$ is a gross return, to which we refer as the incumbents' investment schedule (RRI schedule). Using the definition of quality-adjusted firm size, $x_{t+1} \equiv X_{t+1}/Z_{t+1}$, we can rewrite this return as

$$r^a_{t+1} = \left(\frac{1-\theta}{\theta}\right)\alpha x_{t+1}. \tag{B.16}$$

The expression in (B.4) yields the rate of return to equity in symmetric equilibrium:

$$r^a_{t+1} = \frac{D_{t+1}}{V_t} + \frac{V_{t+1} - V_t}{V_t}. \tag{B.17}$$

Next, using the expression for dividends $D_t = F_t - I_t$ in (B.12), it yields

$$r^a_{t+1} = \frac{F_{t+1} - I_{t+1}}{V_t} + \frac{V_{t+1} - V_t}{V_t}. \tag{B.18}$$

Using the free-entry condition $V_t = \nu X_t$ in (B.8), and multiplying and dividing by Z_t the first two terms on the right-hand side of (B.18), it yields

$$r^a_{t+1} = \frac{F_{t+1}/Z_t - I_{t+1}/Z_t}{\nu X_t/Z_t} + \frac{X_{t+1}/Z_t - X_t/Z_t}{X_t/Z_t}. \tag{B.19}$$

Using the expression for the gross cash flow $F_t = (p_t - 1)X_t - \phi Z_t$, jointly with the constant markup pricing rule $p_t = 1/\theta$, it yields the schedule linking the rate of return to equity one period ahead, r^a_{t+1}, to the current R&D investment rate, i_t:

$$r^a_{t+1} = \left[\frac{[(1-\theta)/\theta]x_{t+1} - \phi - i_{t+1}}{\nu x_t}\right](1 + i_t) + \frac{x_{t+1}(1 + i_t)}{x_t} - 1. \tag{B.20}$$

We refer to (B.20) as the entrants' investment schedule (RRE schedule).

B.3. Loci of Product and Quality Innovation

Here we provide details on the derivation of the PI and QI loci. The PI and QI loci jointly determine the gross growth rate, $z_t \equiv Z_t/Z_{t-1}$, and the quality-adjusted firm size, $x_t \equiv X_t/Z_t$, in the steady state of the model with constant tax rates. In steady state, (B.16) reduces to

$$R^a = \left(\frac{1-\theta}{\theta}\right)\alpha x + 1. \tag{B.21}$$

Next, using the expression for the effective SDF, and realising that in the steady state aggregate consumption grows at the same rate of quality improvement, it yields the QI locus in the (x, z) space:

$$z = \beta(1-\delta)\left[\left(\frac{1-\theta}{\theta}\right)\alpha x + 1\right]. \tag{B.22}$$

Next, in the steady state, (B.20) reduces to

$$R^a = \left[\left(\frac{1-\theta}{\nu\theta}\right) - \frac{\phi + i}{\nu x}\right](1 + i) + 1 + i. \tag{B.23}$$

Using the steady-state expression for the effective SDF and $z = 1 + i$, it yields the PI locus in the (x, z) space:

$$1 = \beta(1-\delta)\left(1 + \frac{1-\theta}{\nu\theta} - \frac{\phi + z - 1}{\nu x}\right). \tag{B.24}$$

B.4. Model Income and Product Accounts

Here we provide details on the calculation of GDP in the model in relation to the US NIPA. In NIPA's accounting methodology, GDP can be measured as: (*i*) the sum of the value added generated at each stage of production ('value-added approach'); (*ii*) the sum of goods and services sold to final users ('expenditures approach') and (*iii*) the sum of income payments and other costs incurred in the production of goods and services ('income approach'). Next, we calculate GDP in the model according to these three different approaches.

B.4.1. Value-added approach

According to the value-added approach, GDP equals the sum of the valued added generated at each stage of production. In the product side of the model accounts, there are two stages of production: (*i*) production of the final good in the final good sector and (*ii*) production of the intermediate good in the corporate sector. Value added (VA) in the final good sector is $\mathrm{VA}_t^{\mathrm{FS}} = Y_t - p_t \tilde{N}_t X_t$, where Y_t is sales of final goods and $p_t \tilde{N}_t X_t$ is the value of intermediate inputs used up in production. (Note that we take the final good as the numéraire, whose price is then normalised to one.) Value added in the corporate sector is $\mathrm{VA}_t^{\mathrm{CS}} = p_t \tilde{N}_t X_t - \tilde{N}_t X_t - \phi Z_t$, where $p_t \tilde{N}_t X_t$ is sales of intermediate goods and $\tilde{N}_t X_t + \phi Z_t$ is production costs. The production technology in the corporate sector requires one unit of final good per unit of intermediate good produced, such that $\tilde{N}_t X_t$ is intermediate expenses on goods used up as inputs into the production of intermediate goods. Note that we treat R&D expenditures in the corporate sector as fixed assets, which is consistent with the current NIPA approach. As a result, in the model, $\mathrm{GDP}_t = \mathrm{VA}_t^{\mathrm{FS}} + \mathrm{VA}_t^{\mathrm{CS}} = Y_t - \tilde{N}_t X_t - \phi Z_t$.

B.4.2. Expenditures approach

According to the expenditures approach, GDP equals the sum of (*i*) *personal consumption expenditures*, (*ii*) *gross private fixed investment*, (*iii*) *change in private inventories*, (*iv*) *net exports of goods and services* and (*v*) *government consumption expenditures and gross investment*. (Note that, in the model, change in private inventories and net exports of goods and services are identically zero.) Consistently with the current NIPA approach, we treat R&D expenditures as fixed assets, such that R&D is recorded as gross private fixed investment. Also, according to the System of National Accounts, 2008 (2008 SNA), R&D is defined as 'creative work undertaken on a systematic basis to increase the stock of knowledge, and use of this stock of knowledge for the purpose of discovering or developing new products, including improved versions or qualities of existing products, or discovering or developing new or more efficient processes of production'. (See http://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf for further details on the treatment of R&D in national accounts.) We classify investment in quality improvements, $\tilde{N}_t I_t$, as R&D expenditures, and sunk entry costs, $\nu X_t \Delta_t^N$, as private fixed investment. As a result, in the model, $\mathrm{GDP}_t = C_t + G_t + \tilde{N}_t I_t + \nu X_t \Delta_t^N$, where C_t and G_t are personal and government consumption expenditures, respectively, and $\tilde{N}_t I_t + \nu X_t \Delta_t^N$ is gross private fixed investment.

B.4.3. Income approach

According to the income approach, GDP equals the sum of the income payments and other costs incurred in the production of goods and services. The recognition of R&D expenditures as gross private fixed investment also affects the income side of the accounts (both in the model and NIPA data) as gross domestic income (GDI) equals GDP. According to the current NIPA approach, R&D expenditures are entirely attributed to corporate profits. Thus, in the income side of the model accounts, we calculate corporate profits as $\tilde{N}_t \Pi_t + \tilde{N}_t I_t$, where Π_t is operating profit. Note that, in the model, $p_t \tilde{N}_t X_t = \theta Y_t$. As a result, in the model, $\mathrm{GDI}_t \equiv \mathrm{GDP}_t = Y_t - \tilde{N}_t X_t - \phi Z_t$.

Appendix C. More on Calibration

C.1. Data Moments and Model Parameters

The constant firm's exit probability in the model, δ, is identified by direct measurement of the average death rate of firms in the US business sector:

$$\text{death rate}_t = \frac{\text{number of firms' deaths}_t}{\text{number of firms}_{t-1}}. \tag{C.1}$$

Data on the total number of firms in the US private sector and firm deaths (defined as the exit of all establishments owned by a firm) are from the U.S. Census Business Dynamics Statistics (BDS) (Excel spreadsheet file `bds_f_all_release.xlsx`). To construct the empirical counterpart of the bond return, R_t^b, we deflate the series `b1ret` (nominal return on one-year US Treasury bonds) using `cpiret` (CPI rate of change), from the Center for Research in Security Prices, available at Wharton Research Data Services. The US long-run growth rate is estimated from the historical real GDP series from U.S. Bureau of Economic Analysis (BEA).

C.1.1. Identification (α, ν, ϕ)

We derive expressions for the R&D-to-GDP ratio and the profit-to-GDP ratio on the BGP. In the model, GDP is $\mathcal{Y}_t = Y_t - \tilde{N}_t X_t - \phi \tilde{N}_t Z_t$. Dividing by output, Y_t, and using the relationship $\tilde{N}_t X_t = \theta^2 Y_t$, we can write the ratio of GDP to output as

$$\frac{\mathcal{Y}_t}{Y_t} = 1 - \theta^2\left(1 + \frac{\phi}{x_t}\right). \tag{C.2}$$

As a result,

$$\frac{\text{R\&D}_t}{\mathcal{Y}_t} = \frac{\tilde{N}_t(Z_{t+1} - Z_t)}{\mathcal{Y}_t} = \frac{\tilde{N}_t(z_{t+1} - 1)Z_t}{(\mathcal{Y}_t/Y_t)(\tilde{N}_t X_t/\theta^2)} = \frac{\theta^2(z_{t+1} - 1)}{[1 - \theta^2(1 + \phi/x_t)]x_t}. \tag{C.3}$$

On the BGP, z_t and x_t are constant, so we remove their time subscripts. Using the above equation, we can write

$$x = \frac{\theta^2}{1 - \theta^2}\left[\frac{z - 1}{\text{R\&D}/\mathcal{Y}} + \phi\right]. \tag{C.4}$$

Equation (C.4) allows us to replace the latent variable of quality-adjusted firm size, x, in terms of the observable R&D-to-GDP ratio. Next, the model's profits-to-GDP ratio is

$$\begin{aligned}
\frac{\text{Profits}_t}{\mathcal{Y}_t} &= \frac{\tilde{N}_t(P_t X_t - X_t - \phi Z_t)}{(\mathcal{Y}_t/Y_t)Y_t} \\
&= \frac{\tilde{N}_t((1/\theta - 1)X_t - \phi Z_t)}{(\mathcal{Y}_t/Y_t)\tilde{N}_t X_t/\theta^2} \\
&= \frac{\theta^2[(1-\theta)x_t/\theta - \phi]}{[1 - \theta^2(1 + \phi/x_t)]x_t},
\end{aligned} \tag{C.5}$$

where we used the pricing equation $p_t = 1/\theta$, and $\tilde{N}_t X_t = \theta^2 Y_t$ in the second equality. Removing the time subscript from the last expression and substituting for x from (C.4), and solving for ϕ

yields

$$\phi = \frac{\theta(1 - \text{Profits}/\mathcal{Y}) - \text{Profits}/\mathcal{Y}}{(\text{R\&D}/\mathcal{Y})/(z-1)}. \tag{C.6}$$

The three moments, the long-run growth rate, z, R&D-to-GDP and the profits-to-GDP, identify ϕ, given that we have already identified θ. Since we have ϕ, (C.4) gives us the value of x. Next, we use the product-innovation locus and the quality-innovation locus in the $(x, z(x))$ space, which we reproduce here for the reader's convenience:

$$z = 1 - \phi + \left[\frac{1-\theta}{\theta} - \frac{\nu(1-\tilde{\beta})}{\tilde{\beta}}\right]x, \tag{C.7}$$

$$z = \tilde{\beta}\left[\left(\frac{1-\theta}{\theta}\right)\alpha x + 1\right]. \tag{C.8}$$

Given that in the first equation above, everything is identified except for ν, and in the second equation, everything is identified except for α, these two equations uniquely pin down ν and α.

To construct the profits-to-GDP ratio, we used the corporate profits before tax (FRED series A053RC1Q027SBEA) and the GDP data (FRED series GDPA: gross domestic product, billions of dollars, annual, not seasonally adjusted). To construct the R&D-to-GDP ratio, we used the R&D data from National Accounts: research and development, billions of dollars, annual, not seasonally adjusted (FRED series Y694RC1A027NBEA) and the FRED series GDPA above.

C.1.2. Identification of γ

Using labour demand (7), $w_t L_t = (1-\theta)Y_t$, and labour supply (9), $\gamma C_t = (1-\tau_t)w_t(1-L_t)$, one obtains equilibrium labour on the BGP using

$$\gamma = \left(\frac{1-L}{L}\right)(1-\tau)\frac{1-\theta}{C/Y}, \tag{C.9}$$

where $L = 0.33$ as per our target and the tax rate is 0.325. The ratio C/Y is obtained from the resource constraint (B.1) combined with the expression for government purchases, G, in (B.14), which on the BGP depends only on the identified parameters so far, and the value of x from (C.4).

C.2. Comparative Statics

The discussion in Appendix C.1 shows that changes in α should mostly affect three moments: (1) the economy's long-run growth rate; (2) the R&D-to-GDP ratio and (3) the profits-to-GDP ratio. Table C.1 shows how a 1%, 5% and 10% change in α affects these three3.tab moments.

C.3. Comparative Dynamics

Figures C.1–C.8 show IRFs for alternative parameterisations of η and ψ. Baseline values of η and ψ are 0.365 and 10.545, respectively. The figures depict the model IRFs with a ±10% and ±20% change in these two parameters.

Figure C.9 shows the economy's response to the Tax Cuts and Jobs Act (TCJA) of 2017 with significantly lower R&D investment adjustment costs. We reduce ψ from 10.545 to 3, keeping

Table C.1. *Knowledge Spillover Parameter.*

	% Changes in α						
	−10%	−5%	−1%	Baseline	+1%	+5%	+10%
Growth rate	0.4%	1.2%	1.8%	2.0%	2.2%	2.8%	3.7%
R&D-to-GDP ratio	0.5%	1.6%	2.4%	2.6%	2.8%	3.6%	4.6%
Profits-to-GDP ratio	7.1%	8.1%	8.8%	9.0%	9.2%	9.9%	10.9%

Notes: This table shows how changes in α affects the relevant moments used in the model's calibration, that is, the economy's long-run growth rate, the R&D-to-GDP ratio and the profits-to-GDP ratio. In the baseline parameterisation, $\alpha = 0.235$. The other parameters are fixed at their baseline values in Table 1.

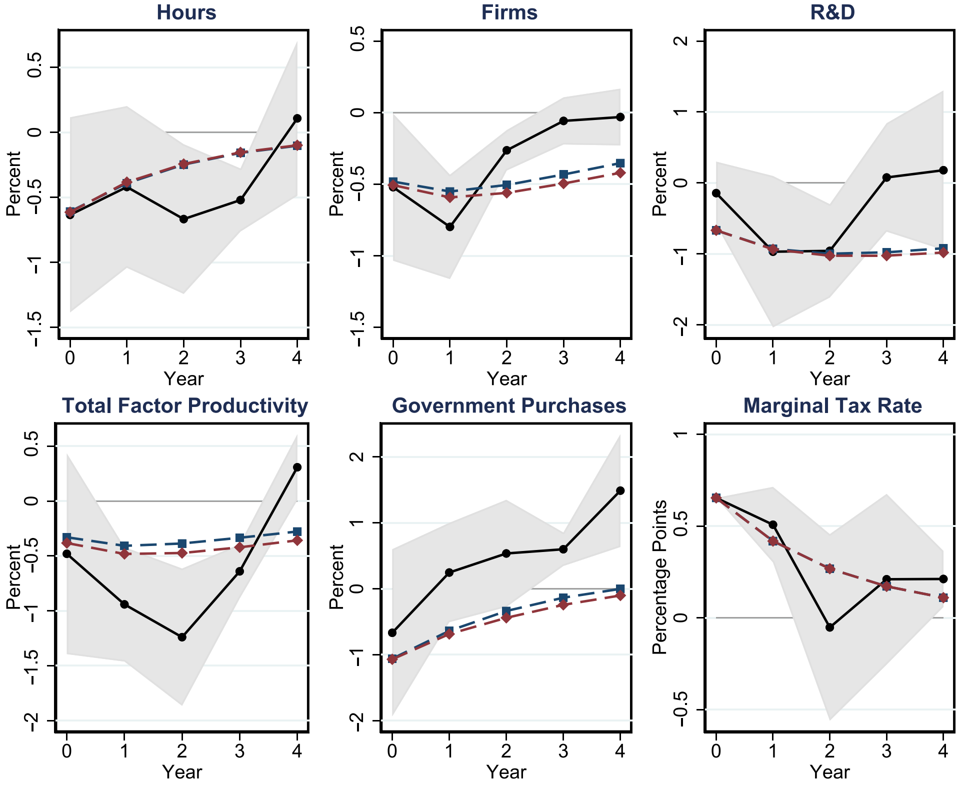

Fig. C.1. *IRFs with Lower Labour Congestion (20% Lower η).*
Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2, the IRFs to an equally sized increase in the labour tax rate in the model for $\eta = 0.365$ (dashed lines with squares) and the IRFs to an equally sized increase in the labour tax rate in the model for $\eta = 0.292$ (dashed lines with diamonds). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

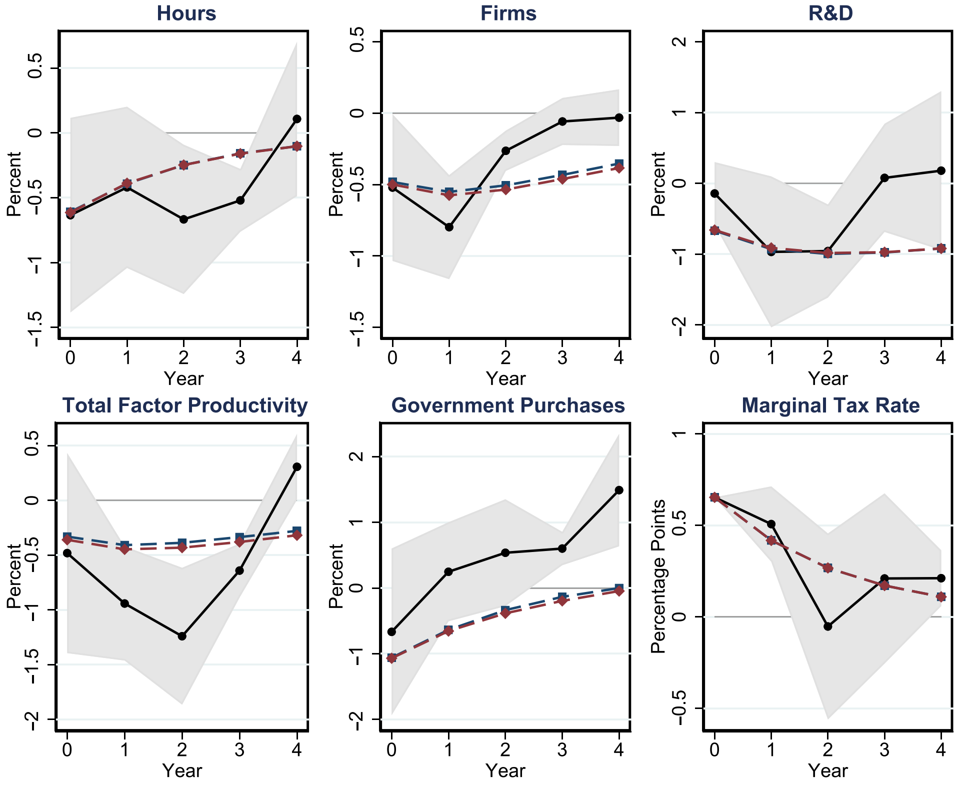

Fig. C.2. *IRFs with Lower Labour Congestion (10% Lower η).*

Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2, the IRFs to an equally sized increase in the labour tax rate in the model for $\eta = 0.365$ (dashed lines with squares) and the IRFs to an equally sized increase in the labour tax rate in the model for $\eta = 0.329$ (dashed lines with diamonds). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

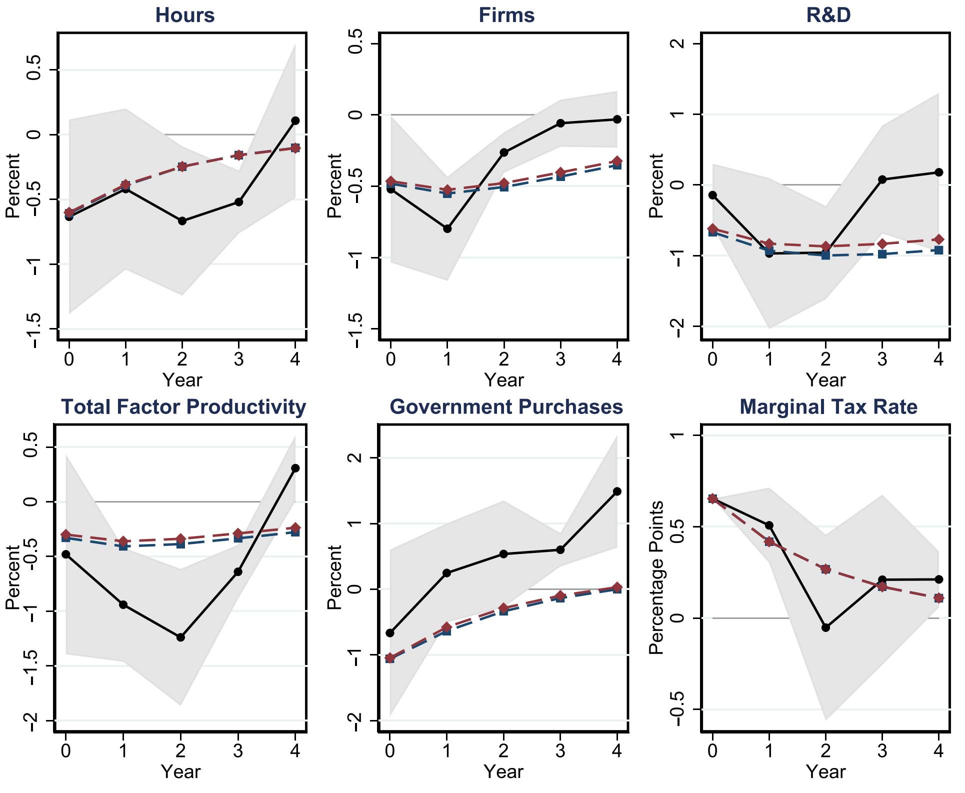

Fig. C.3. *IRFs with Higher Labour Congestion (10% Higher η).*
Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2, the IRFs to an equally sized increase in the labour tax rate in the model for $\eta = 0.365$ (dashed lines with squares) and the IRFs to an equally sized increase in the labour tax rate in the model for $\eta = 0.402$ (dashed lines with diamonds). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

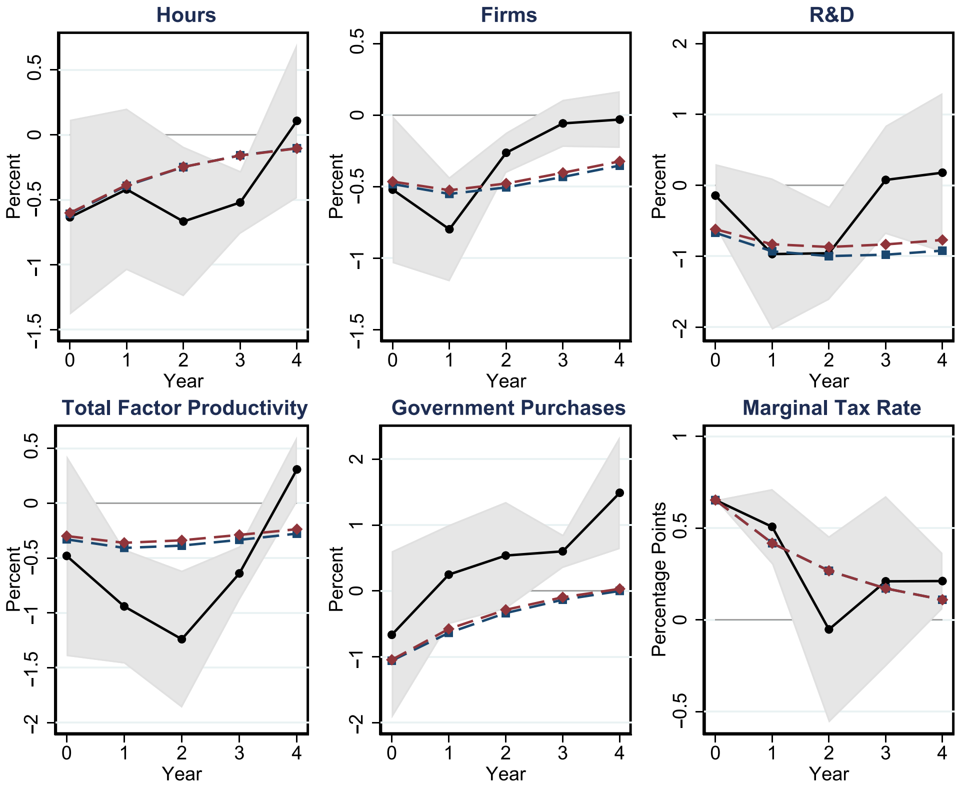

Fig. C.4. *IRFs with Higher Labour Congestion (20% Higher η).*
Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2, the IRFs to an equally sized increase in the labour tax rate in the model for $\eta = 0.365$ (dashed lines with squares) and the IRFs to an equally sized increase in the labour tax rate in the model for $\eta = 0.438$ (dashed lines with diamonds). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

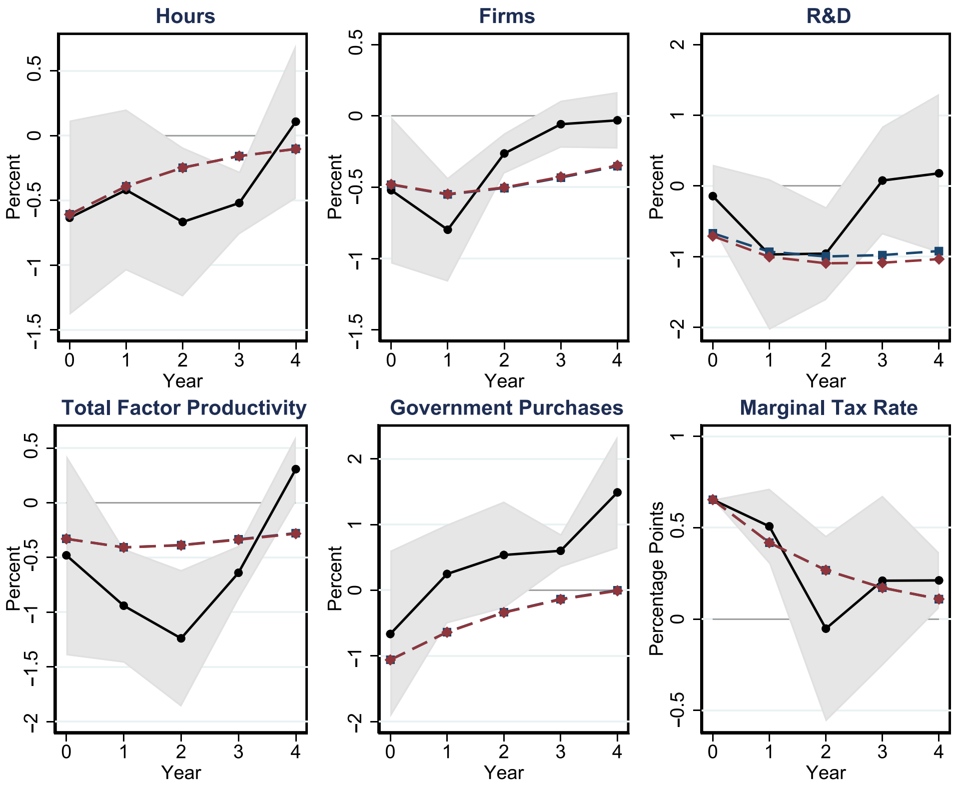

Fig. C.5. *IRFs with Lower Investment Adjustment Costs (20% Lower ψ).*
Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2, the IRFs to an equally sized increase in the labour tax rate in the model for $\psi = 10.545$ (dashed lines with squares) and the IRFs to an equally sized increase in the labour tax rate in the model for $\psi = 8.436$ (dashed lines with diamonds). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

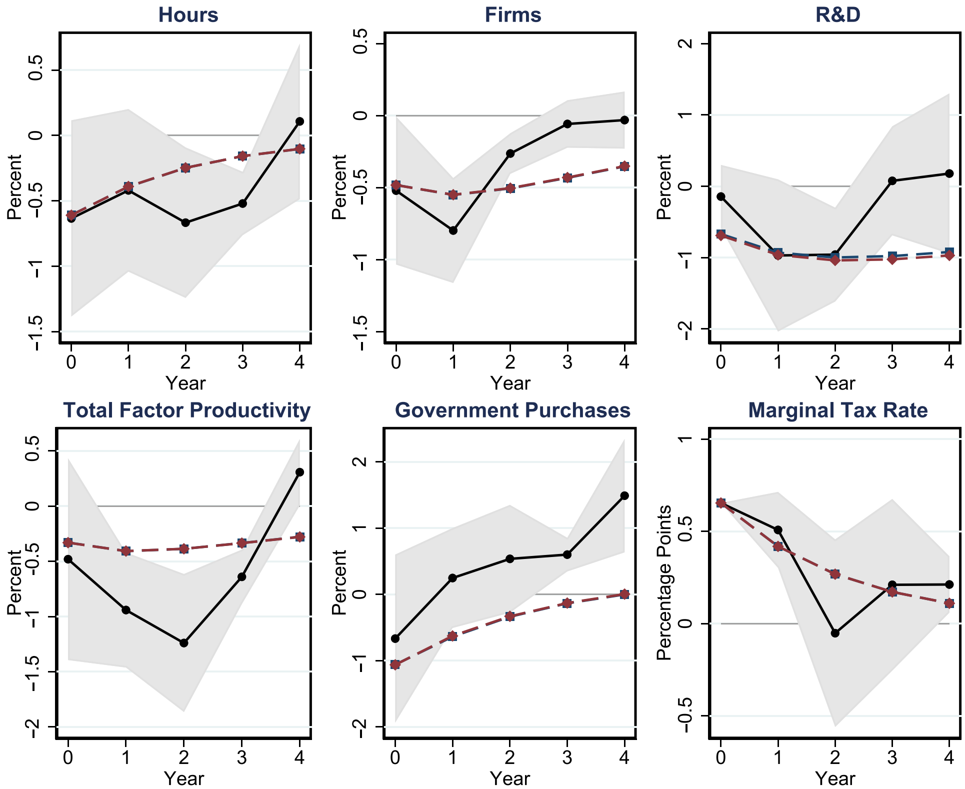

Fig. C.6. *IRFs with Lower Investment Adjustment Costs (10% Lower ψ).*
Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2, the IRFs to an equally sized increase in the labour tax rate in the model for $\psi = 10.545$ (dashed lines with squares) and the IRFs to an equally sized increase in the labour tax rate in the model for $\psi = 9.491$ (dashed lines with diamonds). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

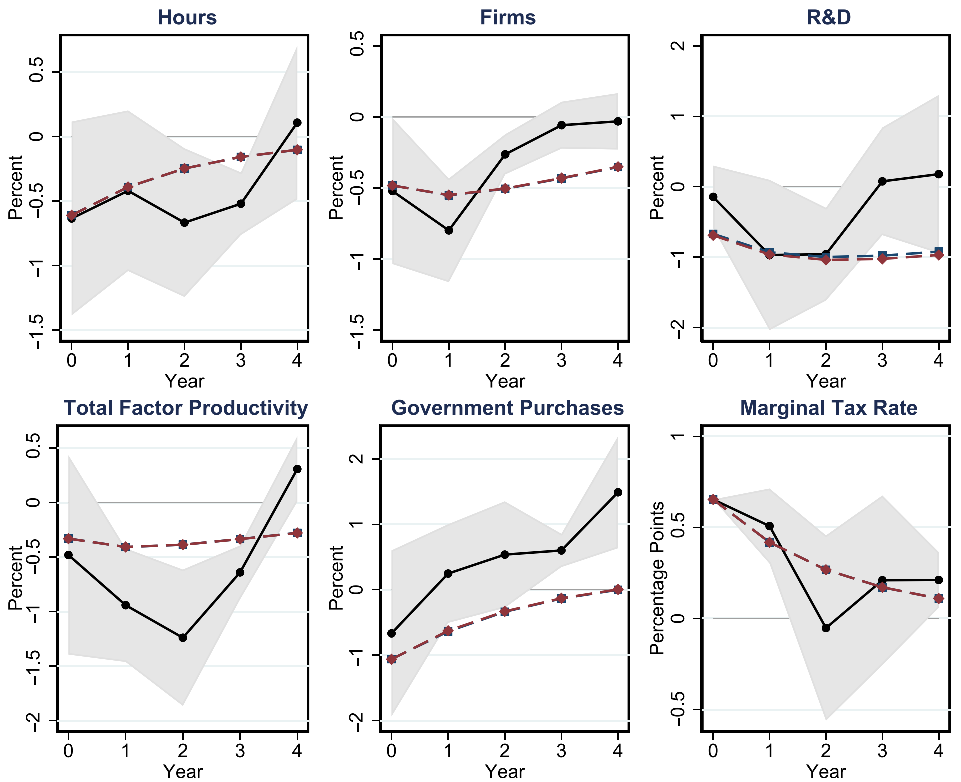

Fig. C.7. *IRFs with Higher Investment Adjustment Costs (10% Higher ψ).*
Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2, the IRFs to an equally sized increase in the labour tax rate in the model for $\psi = 10.545$ (dashed lines with squares) and the IRFs to an equally sized increase in the labour tax rate in the model for $\psi = 11.560$ (dashed lines with diamonds). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

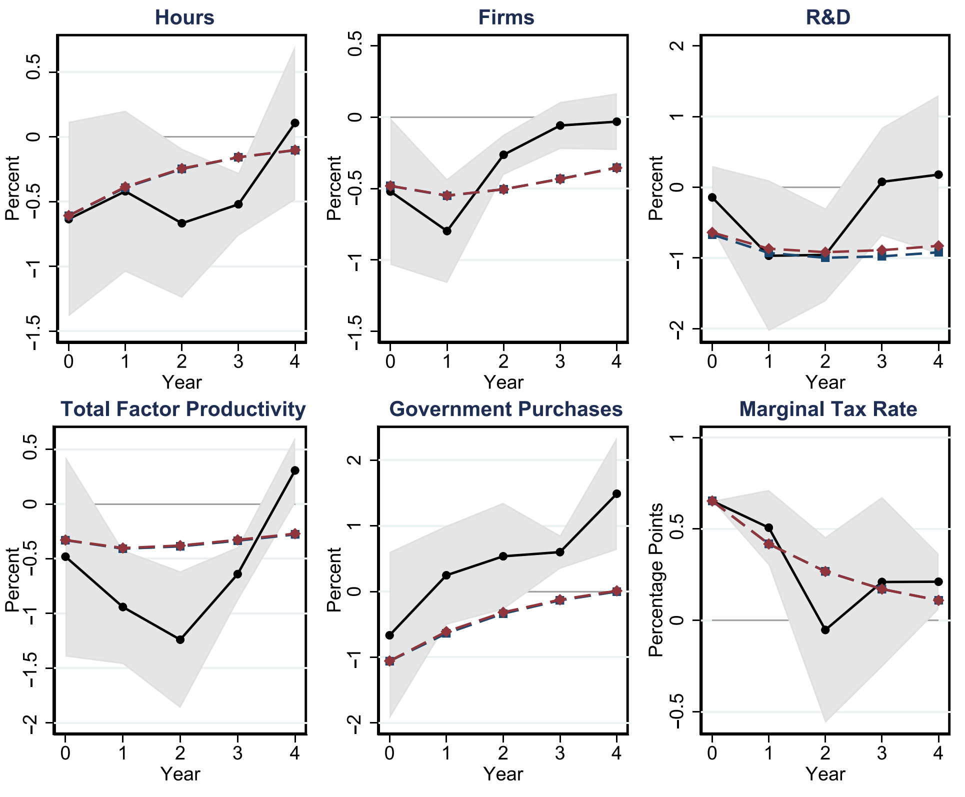

Fig. C.8. *IRFs with Higher Investment Adjustment Costs (20% Higher ψ).*
Notes: The figure shows the empirical IRFs to an AMTR shock (solid lines with circles) as reported in Figure 2, the IRFs to an equally sized increase in the labour tax rate in the model for $\psi = 10.545$ (dashed lines with squares) and the IRFs to an equally sized increase in the labour tax rate in the model for $\psi = 12.654$ (dashed lines with diamonds). Empirical IRFs are estimated using the local projection method of Jordà (2005) and IV regressions. Shaded areas are 90% confidence bands estimated with the HAC-robust residual covariance matrix of Newey and West (1994).

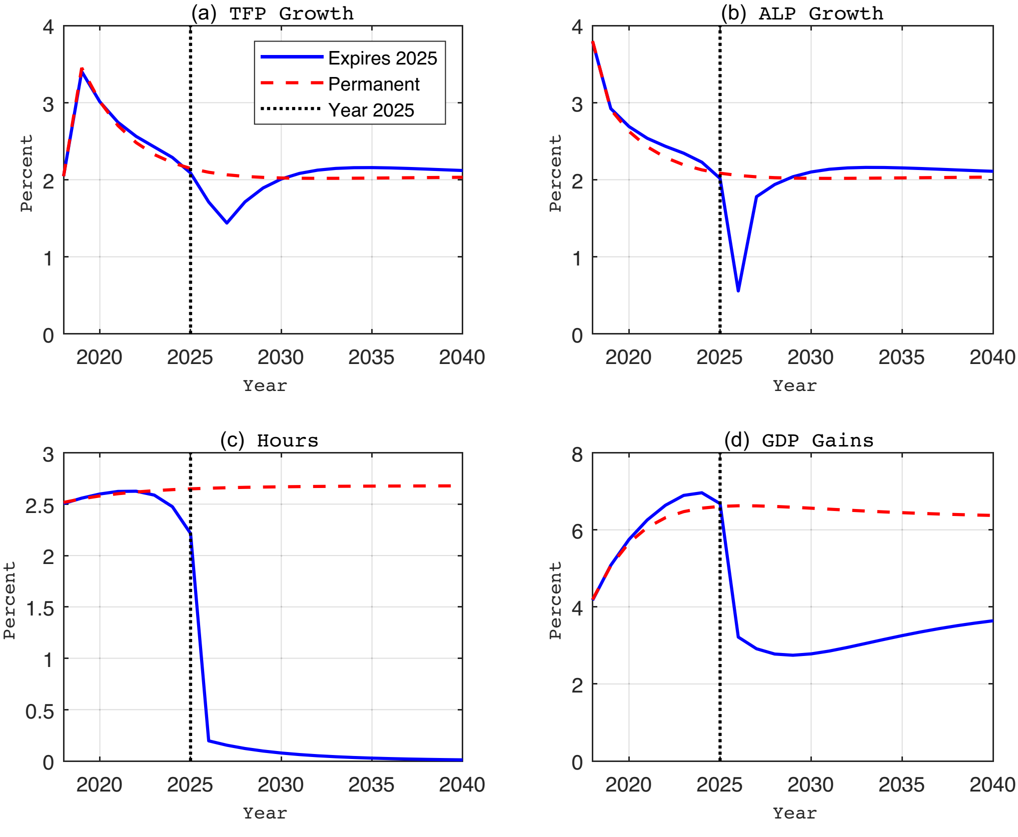

Fig. C.9. *Model Predictions for the Tax Cuts and Jobs Act of 2017.*
Notes: Solid lines show equilibrium paths simulated from the model after a temporary, three percentage point tax cut set to expire in 2025, as in the TCJA of 2017. The model economy is assumed to be on the BGP in 2017 with a labour tax rate of 26%. The tax rate is 23% from 2018 to 2025 and returns to 26% from 2026 onwards. Dashed lines show paths under a permanent three percentage point tax cut, where we feed the model a tax rate of 23% from 2018 onwards. In all panels, the government-purchases-to-GDP ratio remains constant at its 2017 level. Lump-sum transfers adjust to balance the government budget on a period-by-period basis. In this exercise, we consider a significant reduction in the R&D investment adjustment cost parameter and set $\psi = 3$. Other parameters are the same as those used for Figure 6.

other parameters at their baseline values. In addition to serving as a robustness check, this exercise further illustrates the propagation mechanism through which a tax cut affects productivity growth. Note that the GDP gain after 2025 is about 3.7%, as opposed to 2% in Figure 6 of the main text. Moreover, before 2025, Figure C.9 shows an even larger GDP gain relative to the case with higher adjustment costs.

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