Labor Taxes, Market Size, and Productivity Growth*

Domenico Ferraro   Soroush Ghazi   Pietro F. Peretto

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Abstract

How do changes in labor taxes affect innovation and aggregate productivity growth? To answer this question, we propose a quantitative general-equilibrium growth model with product and quality innovation, estimate its parameters, and provide empirical validation for it. We find that a temporary, deficit-financed, cut in flat-rate labor taxes produces a temporary growth acceleration in aggregate productivity, permanently increasing the path of real GDP per capita. These permanent gains are sizable even in the absence of long-run growth effects.

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*Ferraro: Department of Economics, W. P. Carey School of Business, Arizona State University, PO Box 879801, Tempe, AZ 85287, United States (e-mail: domenico.ferraro@asu.edu); Ghazi: Department of Economics, Finance and Legal Studies, Culverhouse College of Business, The University of Alabama, Box 870224, Tuscaloosa, AL 35487, United States (e-mail: sgkalahroudi@culverhouse.ua.edu); Peretto: Department of Economics, Duke University, Box 90097, Durham, NC 27708, United States (e-mail: peretto@econ.duke.edu). The first version of this paper was circulated under the title "Lessons for Tax Reform from an Equilibrium Model of Innovation." First version: January 26, 2019. We thank Aubhik Khan, Todd Schoellman, Gustavo Ventura, and seminar audiences for helpful comments. All errors are our own.

1 Introduction

How do changes in labor taxes affect innovation and productivity growth? To answer this question, we use a quantitative general-equilibrium model with product and quality innovation, estimate its parameters, and provide empirical validation for it. Consistent with novel empirical evidence based on structural vector autoregressions (SVARs), we find that a temporary cut in flat-rate labor taxes produces a temporary acceleration in productivity growth. While this is a transition dynamics phenomenon, it increases the path of real GDP per capita permanently. These permanent gains are sizable even in the absence of long-run growth effects.

Our theoretical analysis is based on three premises. First, flat-rate labor taxes have transitory short-run growth effects, but they are neutral in terms of long-run growth. 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 long periods of time (Easterly and Rebelo, 1993; Stokey and Rebelo, 1995; Mendoza, Milesi-Ferretti and Asea, 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 fully overturn previously enacted tax changes (see Romer and Romer, 2009, 2010, for a history of U.S. tax policy). This has led to substantial variation in average marginal tax rates on labor income (Barro and Sahasakul, 1983; Barro and Redlick, 2011). A quantitative exploration of U.S. tax policy faces then the challenge of taking into account transition dynamics, as well as expectations about future policy changes, that need not necessarily reflect those originally legislated.

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

In Sections 2 and 3, we present a quantitative version of a Schumpeterian growth

[1] For example, in the United States, in 2018, individual income taxes and 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 and gift taxes and 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/.

model without the "scale effect" (see Peretto, 1998; Dinopoulos and Thompson, 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 taxation. In addition, the balanced growth path of the model is consistent with two long-run observations for the post-war U.S. 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; Cociuba, Prescott and Ueberfeldt, 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; Ulku, 2007; Ha and Howitt, 2007; Madsen, 2008; Ang and Madsen, 2011).

Productivity growth is the result of product and quality innovation. In a free-entry equilibrium, entrants create new products whereas incumbents make investments to improve the quality of existing products (see, e.g., Mansfield, 1968; Scherer, 1986; Broda and Weinstein, 2010; Garcia-Macia, Hsieh and Klenow, 2016, for empirical evidence). Market structure is endogenous: the mass of firms and firm size are jointly determined. The mass of firms and average product quality are two aggregate state variables that propagate changes in tax policy.

Firms' entry and quality-improving investments are forward-looking decisions, that depend on their expected rates of return. In equilibrium, such rates of return depend on the expected path of the aggregate labor input and number of firms. Thus, the time path of labor tax rates (and government purchases) after a legislated tax change matters a great deal for the quantitative evaluation of tax policy.

First, flat-rate labor taxes directly affect labor supply via an intratemporal distortion to the consumption-leisure trade-off. Second, the implied changes in hours worked alter incentives to firms' entry, thereby contributing to determine the mass of active firms in the business sector. The time path of the labor input per firm – our operational measure of firm size – is the key determinant of the intertemporal allocation of aggregate innovative investment. This is the "market-size effect" at play in theories of endogenous technical change.[3]

In Sections 4 and 5, we examine the quantitative predictions of the model for the U.S.

[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; Aghion and Howitt, 1992). This prediction is problematic because it means that population growth should produce accelerating per capita real output growth, which is at odds with historical evidence.

[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 U.S. pharmaceutical industry. See also Cohen and Levin (1989) and Cohen (2010) for surveys of the empirical evidence on market structure and innovation.

economy. To this goal, we first estimate the model parameters by matching key moments of U.S. data, then we ask if and to what extent the model reproduces the behavior of key macroeconomic aggregates after large, realized changes in individual income tax rates. To address this question, we feed to the model the *observed* time series of average marginal individual income tax rates and average marginal payroll tax rates, as constructed by Barro and Redlick (2011). We find that the estimated model accounts reasonably well for the observed movements in TFP, labor productivity, market hours worked and per capita number of firms during the "Reagan tax cuts" of the eighties. We stress that the model is estimated to match unconditional moments of the data. Thus, its ability to reproduce part of the observed time-series variation is not hard-wired into the model. On the contrary, it is a successful test of the quantitative theory we propose.

To validate the propagation mechanism embodied in the model, we rely on a large empirical literature that has estimated the aggregate labor supply and per capita GDP growth responsiveness to tax rate changes. In the model, the quantitative impact of tax changes critically depends on the response of the labor input, and how the implied changes in hours worked feed to a productivity growth acceleration/deceleration.

We run regressions on the artificial data simulated from the model and confirm that the sign and the magnitude of the labor and the per capita real GDP growth response to observed changes in labor tax rates are in line with the estimates in the literature (see, e.g., Barro and Redlick, 2011; Mertens and Montiel Olea, 2018). Also, the model accounts well for the impulse response functions (IRFs), as estimated in the context of a proxy-SVAR with narrative identification of tax shocks (Mertens and Ravn, 2013). Specifically, in response to a temporary cut in the average marginal individual income tax rate, market hours worked and the number of firms per capita raise, with a corresponding acceleration of TFP growth. To the best of our knowledge, this is new evidence providing support for the propagation mechanism at work in the model.

After establishing that the model accounts reasonably well for the U.S. experience of the eighties, and that the responses of per capita hours worked, number of firms, and TFP accord well with empirical IRFs, we use the model to quantify the impact of the Tax Cuts and Jobs Act (TCJA) of 2017. We focus on the provisions in TCJA pertaining the individual income tax. Available estimates point to a sizable cut in the average marginal individual income tax rate of nearly 3 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; Mertens, 2018).

The model predicts that a temporary, deficit-financed, 3 percentage points 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 labor productivity growth. At the peak of the response, the model economy experiences an approximately 1.5 percentage points increase in aggregate productivity growth. This temporary growth acceleration translates into a permanent gain in real GDP per capita of 3%, relative to a counterfactual economy without the labor tax cuts in TCJA.

Finally, Section 6 concludes. Appendices A and B contain derivations, the mapping of the model to the National Income and Product Accounts, and details on IRFs' estimation.

1.1 Relation to the Literature

Our paper adds to the endogenous growth literature studying the effects of fiscal policy (see, e.g., King and Rebelo, 1990; Rebelo, 1991; Stokey and Rebelo, 1995; 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 individual 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 to a large extent inadequate for policy evaluation.

Recently, a new wave of papers takes a quantitative approach to gauge the effects of various government policies in the context of models of endogenous technological change (Cozzi and Impullitti, 2010; Ferraro, Ghazi and Peretto, 2017; Akcigit, Hanley and Serrano-Velarde, 2017; Jaimovich and Rebelo, 2017; Atkeson and Burstein, 2019). 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. This paper concerns transition dynamics induced by *temporary* changes in proportional labor taxes. We emphasize work incentives, intertemporal substitution, and market-size effects as quantitatively important channels via which labor taxes impact innovative investment and thereby productivity. We estimate key parameters of the model and provide evidence for the propagation mechanism through which changes in labor taxes affect hours, firm entry and TFP. The model-implied responses of these variables to tax rate changes are comparable to those estimated from the data in the context of SVARs and consistent with a conservative estimate of the aggregate labor supply elasticity.

2 Model

We consider an economy without physical capital. More precisely, there is no capital in the neoclassical sense of a homogenous, durable, intermediate 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.[4]

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 over time through the creation of new products by entrant firms (horizontal or expanding-variety innovation) and the improvements in the quality of existing products by incumbent firms (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 entry and innovate at any point of time. In our setting, entry and quality-improving investments are forward-looking decisions, so that the entire time path of tax rates and government spending matters for equilibrium allocations.

2.1 Environment

Time is discrete and continues forever, indexed by $t = 0, 1, \ldots, \infty$. We consider a closed economy inhabited by a stand-in household that supplies labor services in a competitive labor market. The household faces a standard consumption-savings decision: it chooses consumption, labor supply, bond and financial asset holdings in a spot asset market. Household's income consists of returns on financial assets, a risk-free bond in zero net supply, and labor income.

The production side of the economy consists of a final (or consumption) good sector and an intermediate good sector. The final good sector consists of a single competitive firm that demands intermediate goods and labor to produce a homogeneous final good. The intermediate good sector is monopolistically competitive and it is the source of long-run growth in total factor productivity (TFP) and income per capita.

The market structure of the intermediate good sector is endogenous: the total mass of firms and firm size are jointly determined in free-entry equilibrium. Firms' entry requires

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

the payment of a sunk cost. Upon entry ("horizontal innovation"), firms produce goods that are vertically differentiated by quality. They also invest in research and development (R&D) to improve the quality of their products ("vertical innovation"). R&D at the firm level contributes to the pool of public knowledge that benefits the final good sector in the form of increased TFP (or, equivalently, reduction of unit production costs). This process is self-sustaining and generates exponential growth in the long-run when entry stops and the economy settles into a stable industrial structure.

The government purchases final goods and levies distortionary tax rates on individual labor income at the household level and on the payroll at the firm level. Tax rates vary over time stochastically, which captures the inherent uncertainty in the U.S. tax policy. Lump-sum transfers adjust to balance the budget on a period-by-period basis.

Timeline of events Within a period, events unfold as follows. At the beginning of the period the new values of the tax rates are realized and a mass of firms hit by a "death shock" exit the intermediate good sector. After these events, the household, the firm in the final good sector, and the surviving, incumbent firms in the intermediate good sector make their optimal plans. Entrant firms in the intermediate good sector become active in the next period.

2.2 Households

The economy is inhabited by a stand-in household with a unit mass of infinitely-lived members. Each member is endowed with one unit of time in every period. Household's preferences are described by

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\ln c_t - \gamma \frac{l_t^{1+\vartheta}}{1+\vartheta} \right), \tag{1}$$

where $\mathbb{E}_0$ denotes the mathematical expectation, conditional on time $t = 0$ information, and c_t and l_t are consumption and fraction of time spent at work, respectively. β is the time discount factor, γ parametrizes the disutility of work, and ϑ is the inverse of the Frisch elasticity of labor supply.

Household's expenditures are consumption, c_t, purchases of bonds, b_{t+1}, and equity shares issued by the intermediate good sector, i.e. $\int_0^{N_{t+1}} V_{i,t} \left(s_{i,t+1} - \tilde{s}_{i,t} \right) di$, where $\tilde{s}_{i,t} \equiv (1-\delta) s_{i,t}$ is the number of firm i's shares held at the beginning of period t, $V_{i,t}$ is the price per share, and N_{t+1} is the mass of active 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 per-period (exogenous) probability that a firm exists and Δ_t^N is the mass of new firms entering the intermediate good sector.[5] Household's income consists of wages, $w_t l_t$, returns on bond holdings, $R_{t-1}^b b_t$, distributed dividends, $\int_0^{N_t} D_{i,t}\tilde{s}_{i,t}di$, where $D_{i,t}$ are firm i's distributions per share, and government transfers, Ω_t. The household faces a proportional tax rate, τ_t^l, on labor income, such that total tax liabilities are $\tau_t^l w_t l_t$. Hence, the household's flow budget constraint is

$$c_t + b_{t+1} + \int_0^{N_{t+1}} V_{i,t}\left(s_{i,t+1} - \tilde{s}_{i,t}\right) di = (1-\tau_t^l)w_t l_t + R_{t-1}^b b_t + \int_0^{N_t} D_{i,t}\tilde{s}_{i,t}di + \Omega_t. \quad (2)$$

Household's problem The household takes the tax rate, τ_t^l, government transfers, Ω_t, prices (w_t, R_{t-1}^b, $V_{i,t}$) and distributions, $D_{i,t}$, as given, and it chooses consumption, c_t, labor supply, l_t, bond holdings, b_{t+1}, and equity shares, $s_{i,t+1}$, given the bonds, b_t, and shares, $\tilde{s}_{i,t}$, held at the beginning of the period, to maximize lifetime utility in (1) subject to the budget constraint in (2).

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

$$\gamma c_t l_t^{\vartheta} = (1-\tau_t^l)w_t, \quad (3)$$

and two Euler equations for bond and asset holdings,

$$1 = \mathbb{E}_t\left[M_{t,t+1}R_t^b\right], \quad \text{with} \quad M_{t,t+1} \equiv \beta c_t/c_{t+1}, \quad (4)$$

$$V_{i,t} = \mathbb{E}_t\left[\tilde{M}_{t,t+1}\left(D_{i,t+1} + V_{i,t+1}\right)\right], \quad \text{with} \quad \tilde{M}_{t,t+1} \equiv \beta(1-\delta)c_t/c_{t+1}, \quad (5)$$

where $M_{t,t+1}$ is the stochastic discount factor (SDF) between period t and $t+1$, and $\tilde{M}_{t,t+1}$ is an effective SDF, modified to account for the probability $1-\delta$ that a firm survives from the current to the next period.

2.3 Production and Innovation

The business sector produces a final, homogenous consumption good, and a continuum of intermediate goods differentiated by quality. The final good is the numéraire, so that its price is set to one. The final good has four uses: (i) private and public consumption; (ii)

[5] A positive exit probability is required for the model to have symmetric dynamics in the neighborhood of the deterministic steady state of the economy.

input into the production of intermediate goods; (iii) investment in quality improvements of existing intermediate goods; (iv) entry and creation of new intermediate goods.

2.3.1 Final Good Production

The final good sector is competitive and consists of a firm that uses intermediate inputs, $X_{i,t}$, that are vertically differentiated by their quality, $Z_{i,t}$, and labor input, L_t, to produce the final good, Y_t. The production technology is

$$Y_t = \int_0^{\tilde{N}_t} X_{i,t}^{\theta} \left(Z_{i,t}^{\alpha} Z_t^{1-\alpha} \frac{L_t}{\tilde{N}_t^{\eta}} \right)^{1-\theta} di, \tag{6}$$

where $\tilde{N}_t \equiv (1-\delta)N_t$ 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 the degree of congestion (or rivalry) of labor across intermediate goods. On the one hand, for $\eta = 0$ there is no congestion as labor can be shared by all intermediate goods with no productivity loss. This is the case of extreme economies of scope in labor use that in equilibrium manifest as strong social increasing returns to product variety. On the other hand, for $\eta = 1$ there is full congestion. This is the case of no economies of scope and no social returns to variety.

The technology in (6) implies that the productivity of the labor 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 is the defining feature of vertical product innovation: higher-quality intermediate goods perform similar functions to those performed by lower-quality goods, however, they increase the efficiency of the production process and, as a result, they reduce unit costs of production.

Final producer's problem The final producer takes the intermediate good i's quality, $Z_{i,t}$, and average quality of intermediate goods, Z_t, as given and maximizes 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 labor equal to its effective price, $(1+\tau_t^f)w_t$, where τ_t^f is the payroll tax rate. Perfect competition in the final good sector and the production technology in (6) imply that profits are zero.

The final producer's problem yields a demand for intermediate goods,

$$X_{i,t} = \left(\frac{\theta}{p_{i,t}}\right)^{\frac{1}{1-\theta}} Z_{i,t}^{\alpha} Z_t^{1-\alpha} \frac{L_t}{\tilde{N}_t^{\eta}}, \tag{7}$$

and a demand for labor,

$$(1+\tau_t^f) w_t L_t = (1-\theta) Y_t. \tag{8}$$

2.3.2 Intermediate Good Production

The intermediate good sector is monopolistically competitive and consists of firms that produce differentiated intermediate goods. Market structure is endogenous, i.e., the mass of firms and firm size are determined in free-entry equilibrium. Intermediate producers invest to improve product quality. Returns to quality-improvement investments come in the form of monopoly rents in the imperfectly competitive product market. Quality improvements are the source of long-run growth in income per capita.

An incumbent firm 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 price, respectively. An incumbent firm can upgrade the quality of its own intermediate good by investing $I_{i,t}$ units of final output:

$$Z_{i,t+1} = Z_{i,t} + I_{i,t}. \tag{9}$$

Incumbent's problem The incumbent, intermediate producer takes the demand curve for intermediate goods (7) and the law of motion for quality (9) as given, and it 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 maximize the cum-dividend value of the firm, $D_{i,t} + V_{i,t}$.

Iterating forward the intertemporal condition for asset holdings (5), 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 distributed dividends,

$$V_{i,t} = \mathbb{E}_t \sum_{j=1}^{\infty} \tilde{M}_{t,t+j} D_{i,t+j}, \tag{10}$$

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

$$1=\mathbb{E}_t\left\{\tilde{M}_{t,t+1}\left[\left(\frac{1-\theta}{\theta}\right)\frac{\alpha X_{i,t+1}}{Z_{i,t+1}}+1\right]\right\}. \tag{11}$$

Entrant's problem Firms' entry in the intermediate good 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 out with a given range of intermediate goods, each supplied by a firm. Because of the sunk entry cost, entering firms do not find profitable to supply an existing good in Bertrand competition with the incumbent monopolists, but they introduce 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 enters the intermediate good sector in the current period starts operating and so paying out dividends next period. Entrant firms finance entry by issuing equity and they enter at the average quality level, Z_t. This is a simplifying assumption that supports the symmetry of the equilibrium.

2.4 Government

The government purchases final goods and finances spending by levying distortionary taxes and it balances the budget period-by-period with lump-sum transfers. Hence, the government's budget constraint reads $G_t+\Omega_t=T_t$, where G_t is net-of-transfers spending (or, equivalently, public consumption), Ω_t denotes lump-sum transfers, and $T_t=\tau_t^l w_t l_t+\tau_t^f w_t L_t$ is tax revenues. As standard in the literature, government spending is modeled 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 modeled as a "pure waste," such that they do not affect either the marginal utility of private consumption or production. Here we focus on the effects of distortionary income taxation.

3 Equilibrium

We now turn to the general equilibrium of the model. Since the equilibrium is symmetric, henceforth, 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 labor and asset market requires $l_t=L_t$ and $s_t=1$, 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,

$$C_t + G_t + \mathcal{I}_t + \mathcal{Q}_t = Y_t, \tag{12}$$

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). (See Appendix A for the full list of equilibrium conditions.)

3.1 Determinants of the Labor Input

We now turn to discuss the intratemporal trade-offs that drive the determination of labor. In setting the supply of labor, the household equates the marginal rate of substitution (MRS) between consumption and leisure to the effective price of leisure. In our economy, the consumption good is the numeraire such that the wage represents the relative price of leisure to consumption. Individual income tax rates introduce a wedge between the MRS and the wage:

$$\gamma L_t^{\vartheta} C_t = (1 - \tau_t^l) w_t. \tag{13}$$

Equation (13) describes an upward-sloping labor supply curve, with a Frisch elasticity of $1/\vartheta$. Notice that in the baseline formulation of the model, tax revenues are only partially rebated to the household as they finance government consumption. Hence, changes in labor income tax rates have income effects.

To provide insight into the equilibrium labor response to tax changes, it is useful to combine household's labor supply (13) and labor demand of the final good producer (8), so that

$$\gamma L_t^{1+\vartheta} = \left(\frac{1 - \tau_t^l}{1 + \tau_t^f} \right) \frac{1 - \theta}{C_t / Y_t}. \tag{14}$$

Changes in the tax rates (τ_t^l, τ_t^f) have a direct impact on the aggregate labor input through standard labor supply/demand forces, and an indirect equilibrium effect through the aggregate consumption-to-output ratio, C_t/Y_t. The extent to which C_t/Y_t responds to changes in either τ_t^l or τ_t^f, or both, critically depends on the response of the business sector, which takes place through changes in entrants' investment in firm creation (net firms' entry/exit) and incumbents' investment in quality improvements.

3.2 Determinants of Product and Quality Innovation

We now turn to discuss the intertemporal trade-offs that determine product and quality innovation. In the model, quality-improving innovation is driven by the forward-looking investment behavior of individual firms. In making an investment plan, a typical firm trades off the cost of diverting resources from current profits with the benefit of raising gross cash flows in the future. Entrants anticipate that after incurring the sunk entry cost, they will face the same trade-offs faced by the incumbents. These are inherently dynamic decisions, which underscores the role played by the private sector expectations about the future path of income and payroll tax rates.

To provide intuition into the inner workings of the model, it is useful to study the asset market equilibrium in terms of the rate of return to incumbents (RRI) and the rate of return to entrants (RRE). We interpret RRI and RRE as investment schedules in the (i_t, r^a_{t+1}) space, where $i_t \equiv I_t/Z_t$ is the current R&D investment rate and r^a_{t+1} is the rate of return to firms' equity one period ahead. The intersection of the RRE and RRI schedules describes the investment decision of the private sector as implied by no arbitrage. (See Appendix A for details on the derivation of the RRI and RRE schedules.)

Quality-improving investment In symmetric equilibrium, the first-order condition for quality-improving investment (11) reduces to

$$1 = \mathbb{E}_t \left\{ \tilde{M}_{t,t+1} \left[\left(\frac{1-\theta}{\theta} \right) \alpha x_{t+1} + 1 \right] \right\}, \tag{15}$$

where $x_{t+1} \equiv X_{t+1}/Z_{t+1}$ measures quality-adjusted firm size, which determines firms' gross profitability through its relationship with quality-adjusted gross cash flow,

$$f_{t+1} \equiv F_{t+1}/Z_t = (p_{t+1} - 1)\, x_{t+1} - \phi, \tag{16}$$

where $p_{t+1} = 1/\theta$ is the unit output price and ϕ is the parameter governing the extent of fixed operating costs. Note that the investment decision at the individual firm-level is a bang-bang problem, so that (15) has to be interpreted as an investment "indifference" condition at the aggregate level. Combining the household's intertemporal condition (5) with the firm's intertemporal condition for quality-improving investment (15), yields the

RRI investment schedule:

$$r_{t+1}^{a} = \left(\frac{1-\theta}{\theta}\right)\alpha x_{t+1}. \tag{17}$$

Note that the RRI investment schedule (17) is a flat line in the (i_t, r_{t+1}^a) space. Again, this reflects the bang-bang property of the investment problem at the individual firm-level.

Firms' entry In symmetric equilibrium, the expression for the rate of return to equity jointly with the free-entry condition $V_t = \nu X_t$ yields the RRE investment schedule:

$$r_{t+1}^{a} = \underbrace{\left[\frac{\left(\frac{1-\theta}{\theta}\right)x_{t+1} - \phi - i_{t+1}}{\nu x_t}\right](1+i_t)}_{\text{dividend-price ratio}} + \underbrace{\left[\frac{x_{t+1}\left(1+i_t\right)}{x_t} - 1\right]}_{\text{capital gains}}. \tag{18}$$

Note that the RRE schedule (18) is an upward-sloping line in the (i_t, r_{t+1}^a) space. Higher rates of return to equity next period are associated to higher rates of investment in R&D today. Such a positive relationship materializes through two channels. Everything else equal, a higher investment rate today is associated to (i) a higher dividend-price ratio tomorrow, and to (ii) an appreciation of the market value of the intermediate good sector.

Discussion Income and payroll tax rates have no direct effect on R&D investment, but only an indirect equilibrium effect that operates through quality-adjusted firm size and aggregate labor, as described by the relationship $x_{t+1} \propto L_{t+1}/\tilde{N}_{t+1}^{\eta}$. Next period labor and number of firms in the intermediate good sector are equilibrium variables, that are out of control of the individual firm. Individual firms take future gross profitability f_{t+1} as a signal about the future prospects of aggregate demand for their products, X_{t+1}, and thereby of quality-adjusted firm size, x_{t+1}. In sum, the transmission mechanism of tax changes to investment in quality improvements operates through two channels: (i) changes in income and payroll tax rates directly affect labor in the form of *intratemporal* disturbances to the consumption-leisure trade-off; (ii) equilibrium dynamics in aggregate labor drives firms' entry, thereby determining the mass of firms in the intermediate good sector. The implied dynamics in the labor input *per firm* are the key driving force of the *intertemporal* allocation of aggregate, quality-improving investment.

3.3 Determinants of Long-Run Growth

Along a balanced growth path (BGP) with constant tax rates, the growth rate of output per capita is determined by a low-dimensional system, that links 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 system consists of a product innovation (PI) locus that captures the incentives to firms' entry,

$$z = 1 - \phi + \left[\frac{1-\theta}{\theta} - \frac{\nu\left(1-\tilde{\beta}\right)}{\tilde{\beta}}\right] x, \tag{19}$$

and of a quality innovation (QI) locus that captures the incentives to quality-improving investment of incumbent firms,

$$z = \tilde{\beta}\left[\left(\frac{1-\theta}{\theta}\right)\alpha x + 1\right], \tag{20}$$

where $\tilde{\beta} \equiv (1-\delta)\beta$ is an effective time discount factor, that takes into account that with probability $1-\delta$ a firm survives to the next period. (See Appendix A for details on the derivation of the PI and QI loci.)

The PI locus (19) describes the steady-state quality-adjusted R&D investment rate $I_t/Z_t = z_t - 1$ that equalizes the rate of return to entry to the rate of return to quality-improving investment, given the value of x that both entrants and incumbents expect to achieve in equilibrium. The QI locus (20) describes instead the steady-state investment rate that incumbent firms 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. Figure 1 illustrates the determination of the steady state of the model based on our baseline parametrization, which we discuss at length in Section 4.3 below.

Existence and stability of the steady state require an intercept condition that the PI curve starts out below the QI curve and a slope condition that the PI curve is steeper than the QI curve. Together they imply that a stable steady state (x^*, z^*) exists with the PI curve cutting the QI curve from below. In order to see the stability of such steady state, notice 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 line is above the QI line to the immediate right of the intersection). This spurs entry and increases the number of firms. Since x is inversely related to the number of firms, x then falls forcing the system to revert back to steady-state value x^*.

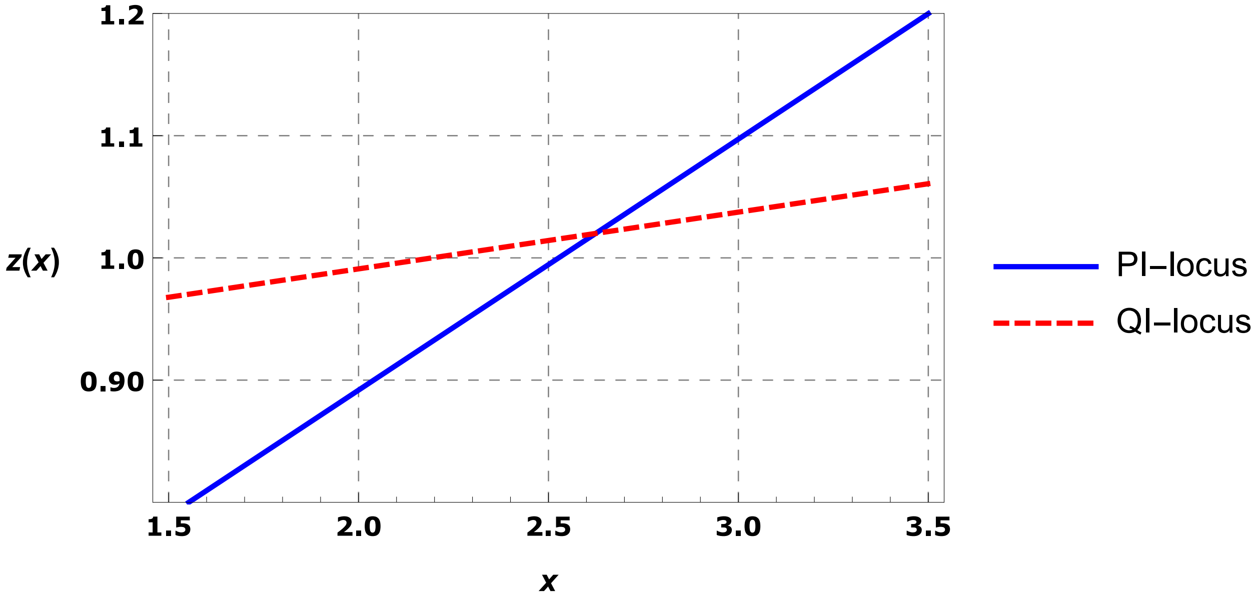

Figure 1: Determination of Steady-State Growth Rate of Quality Improvement

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 equalize the rate of return to entry to the rate of return to quality-improving investment, given the value of x_t that both entrants and incumbents expect to achieve in equilibrium. The QI locus (dashed line) describes the gross growth rate of quality improvement, z_t, that incumbent firms generate given the quality-adjusted firm size, x_t, that they expect to achieve in equilibrium. See Section 4.3 for further details on the baseline parametrization of the model.

In the model, the steady-state growth rate of quality improvement, z^*, is the only driver of aggregate TFP and real GDP growth. This result is due to the presence of fixed operating costs. An ever expanding number of products puts pressure on the economy's aggregate resources by duplicating fixed costs, which in turn makes firms' entry, and so expanding-variety innovation, irrelevant for long-run productivity growth.

Here we stress that neither τ_t^l nor τ_t^f enter the determination of the steady-state rate of quality improvement, z^*, in the system (19)-(20). Explaining why this happens is key to understanding the transmission mechanism of tax policy embodied in the model. The PI and QI curves capture the insight that firms' entry and R&D investment decisions by incumbent firms do not directly respond to changes in τ_t^l and/or τ_t^f, but only indirectly through changes in quality-adjusted firm size. A permanent change in either tax rate affects the equilibrium labor input, and thereby the aggregate demand for intermediate goods. While these *market-size* effects are present in transition dynamics, they are fully sterilized in the long-run by the net entry/exit of firms. To see this, (1) fix the number of firms, then a change in either tax rate affects the quality-adjusted firm's size, x, and thereby incentives to 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 incumbent firms changes, the mass of firms endogenously adjusts (via net entry/exit) to bring the economy back to the initial steady-state level of firm size, x^*. As a result, the adjustment process through firms' entry fully sterilizes the long-run growth effects of the initial tax change.

4 Taking the Model to the Data

In this section we take the model to the data. In Section 4.1, we begin with a brief narrative of post-war U.S. fiscal policy. In Section 4.2, we map the model to the national income and product accounts (NIPA). In Section 4.3, we turn to estimating model parameters related to preferences and technology.

4.1 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 as temporary, mainly motivated by the current state of the business cycle. Other changes were part of major tax reforms, e.g., the Tax Reform Act (TRA) of 1986. By contrast, government purchases as share of GDP have been fairly stable since the Korean War of 1950-1953. Here we describe the time-series behavior of individual income tax rates and government purchases-to-GDP ratios, that we later use as model inputs in our quantitative experiments.

Individual income tax We view the average marginal tax rate (AMTR), as constructed by Barro and Redlick (2011), as a measure of the overall distortion to labor supply. AMTR is the sum of the average marginal individual income tax rate (AMIITR) and the average marginal payroll tax rate (AMPTR). The construction of the AMTR is based on a notion of labor income that includes wages, self-employment, partnership, and S-corporation income. Panels A through C of Figure 2 show the time series of AMTR and its components.

Few remarks are in order. First, the time-series average of the 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 percent range over roughly ten years from 1960 to 1970. In the 1970s, AMTR sharply rises from 25% towards the post-war peak of 38% in the early-1980s. This acceleration was primarily due to the bracket creep effects from the rising inflation during the Great Inflation of the 1970s. After the 1980s, the sustained rises in the Federal Insurance Contributions Act (FICA) tax have been almost entirely offset by reductions in the federal individual income tax rates, which have remained in the 20-25 percent range since then. 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), the bulk of this year-to-year variation is driven by statutory changes in federal individual income taxes. Consistently with 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).

Government purchases as a share of GDP In addition to time-varying tax rates, the private sector also faces government purchases of final output that vary over time. The government spending-to-GDP ratio (GRATIO) in the model g_t is measured as GRATIO $=$ GOV/GDP, where GOV is government consumption expenditures and gross investment, that includes federal (national defense plus non-defense), state and local government level (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.

Panel D of Figure 2 shows the time series for GRATIO. For the post-war period, the mean GRATIO is roughly 21 percent. The GRATIO was below 20 percent until 1950. It sharply raised from 17 percent in 1950 to the post-war peak of nearly 25 percent in 1953. Such a surge in government spending is the result of the increase in national defense expenditure due to the Korean War of 1950-1953. To meet the financing needs for defense expenditure, the Revenue Act of 1950 raised the statutory top corporate income tax rate from 38 to 42 percent in 1950 and to 52 percent in 1952. Since the mid-1950s, government spending has slowly declined and represents 18 percent of GDP in 2014.

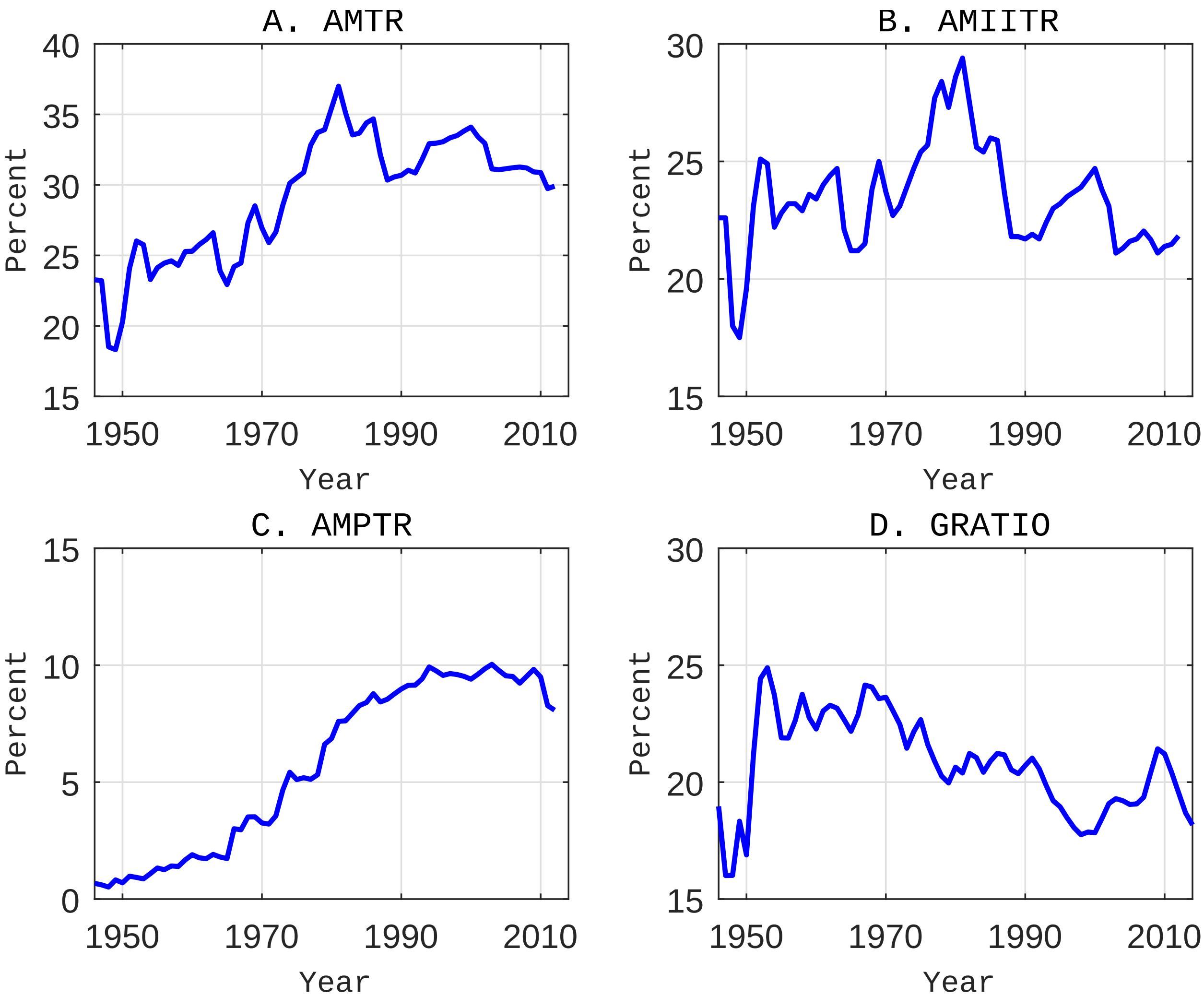

Figure 2: Post-War Fiscal Policy in the United States

Notes: Panel A shows the average marginal tax rate (AMTR), that equals the average marginal individual income tax rate (AMIITR), as shown in panel B, plus the average marginal payroll tax rate (AMPTR), as shown in panel C. Panel D shows the government spending-to-GDP ratio (GRATIO).

4.2 Mapping the Model to NIPA

The model counterpart of the U.S. national income and product accounts (NIPA) implies the following split of gross output between GDP and intermediate expenses:

$$\underbrace{\underbrace{C_t + G_t}_{\substack{\text{private + public}\\ \text{consumption}}} + \underbrace{\tilde{N}_t I_t}_{\substack{\text{product quality}\\ \text{investment (R\&D)}}} + \underbrace{\nu X_t \Delta_t^N}_{\substack{\text{firm creation}\\ \text{investment}}}}_{\text{GDP}} + \underbrace{\underbrace{\tilde{N}_t X_t}_{\substack{\text{input}\\ \text{costs}}} + \underbrace{\phi \tilde{N}_t Z_t}_{\substack{\text{operating}\\ \text{costs}}}}_{\text{intermediate expenses}} = \underbrace{Y_t}_{\substack{\text{gross}\\ \text{output}}}. \tag{21}$$

We include R&D expenditures in the calculation of GDP. This is consistent with the NIPA approach. Since the 2013 NIPA release, BEA recognizes expenditures by business, government, and nonprofit institutions on R&D as fixed assets, which are recorded as investment in GDP. In the previous NIPA approach, expenditures on R&D by business—whether purchased from others or carried out in-house—were treated as intermediate expenses used up during production of other goods and services rather than as capital expenses that generate future income and product. (See Appendix A for further details on the calculation of GDP in the model related to the U.S. national accounts.)

4.3 Parametrization

We are to assign values to 9 parameters describing preferences and technology. A model period is taken to be a year. We exogenously set the value of ϑ, which pins down the Frisch elasticity of labor supply, based on previous work and micro data. We then estimate the remaining parameters $(\beta, \delta, \theta, \eta, \alpha, \nu, \gamma, \phi)$ to match key moments of postwar U.S. data and the impact response of TFP to a tax rate shock, as identified in the context of a proxy-SVAR. Table 1 reports the parameter values.

As standard in dynamic general equilibrium models, none of the parameters has a one-to-one relationship to a specific moment. Yet, 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: Parameter Values

Parameter	Description	Value
A. Preferences		
β	Time discount factor	0.983
γ	Disutility of work	0.682
B. Technology		
θ	Elas. substitution int. goods	0.818
η	Labor congestion	0.694
α	Knowledge spillovers	0.232
δ	Firm exit probability	0.087
ν	Sunk entry cost	0.155
ϕ	Fixed operating cost	0.519

4.3.1 Exogenously Set Parameter

Frisch elasticity We set the parameter $\vartheta = 1$ so that the Frisch elasticity of labor supply is one. This is a conservative estimate (see Chetty et al., 2012, for a survey of available empirical estimates). Disciplining the labor elasticity is important for our measurement, as the magnitude of the labor response to tax changes is a key element of the transmission mechanism of tax policy embodied in the model. Later, we will further discuss the extent to which the magnitude of the labor response to the observed tax changes compares with available empirical estimates.

4.3.2 Estimated Parameters

We estimate the vector of model parameters $\Gamma = (\delta, \beta, \eta, \theta, \alpha, \nu, \gamma)$ using the generalized method of moments (GMM) procedure (Hansen, 1982; Hansen and Singleton, 1982). We then discipline the parameter ϕ using the IRF of TFP estimated from proxy-SVARs. Given the other parameter values, the value of ϕ is set to match the impact response of TFP to an identified marginal tax rate shock. (See Appendix B for details on the estimation of the proxy-SVAR.)

Data moments We consider a just-identified system of equations and estimate the 7 model parameters in the vector Γ using 7 moment conditions implied by our model. In doing so, we use the following time series:

1. Firms' exit rate in the business sector;
2. Real rate of return on 1-year Treasury bonds;
3. Real per capita consumption growth;
4. Market hours worked per capita;
5. Number of firms per capita in the business sector;
6. Average marginal tax rate;
7. Labor share of GDP;
8. Corporate profits' share of GDP;
9. R&D share of GDP;
10. Consumption share of GDP.

Moment conditions & parameter identification In implementing our estimation, we face the challenge that some key variables in the model are unobservable. Notably, quality-adjusted firm size and product quality growth are *latent* variables that cannot be readily measured from the data. Our strategy for dealing with this issue is as follows. We replace quality growth with its long-run value of 2%, that is, $z_{ss} = 1.02$. Given the long-run value of quality growth, we find an expression implied by the model that describes the quality-adjusted firm size only in terms of observables. Then, we write the moment conditions in terms of observables only.

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

$$\text{death rate in year } t = \frac{\text{number of firms' deaths in year } t}{\text{number of firms in year } t}. \tag{22}$$

Data on the total number of firms in the U.S. 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) database, available at https://www.census.gov/ces/dataproducts/bds/data.html (see Excel spreadsheet file `bds_f_all_release.xlsx`).

The time discount factor, β, is identified by the bond pricing equation,

$$1 = \mathbb{E}_t \left[\beta \left(\frac{c_t}{c_{t+1}} \right) R_t^b \right]. \tag{23}$$

To construct the empirical counterpart of the bond return, R_t^b, we deflate the series `b1ret` (nominal return on 1 year U.S. Treasury bonds) using `cpiret` (CPI rate of change), from the Center for Research in Security Prices (CRSP), available at Wharton Research Data Services (WRDS). The ratio c_t/c_{t+1} is the inverse of per capita real consumption growth rate, that is constructed using the time series available at the Federal Reserve Economic Data (FRED) website at https://fred.stlouisfed.org/. The real consumption growth rate is the FRED series `DPCERL1A225NBEA` (real personal consumption expenditures, percent change from preceding period, annual, not seasonally adjusted). The population growth rate is constructed using the FRED series `LFWA64TTUSA647S` (working age population of 15-64 years old, annual, not seasonally adjusted).

To identify the congestion parameter η, we use the fact that $X_t/Z_t = \theta^{\frac{2}{1-\theta}} L_t/N_t^{\eta}$, and hence, on the balanced growth path we have

$$\Delta L_t = \eta \Delta N_t, \tag{24}$$

where Δ denotes the growth rate. Since N_t is a predetermined variable, we can use ΔN_t itself as the instrument to identify the parameter η, similar to the OLS regression of ΔL_t on ΔN_t without a constant. In the model, population is normalized to one, such that L_t is to be interpreted as per capita hours worked. Data on U.S. total hours worked by the civilian population are from Cociuba, Prescott and Ueberfeldt (2018) and available at https://sites.google.com/site/simonacociuba/research (see Excel spreadsheet file `CPU_Data_construction.xlsx`). Similarly, the number of firms N_t must be interpreted as the number of firms per capita. We use BDS data and divide the number of firms by the non-institutional population of 16-64 years old to construct the time series of the number of firms per capita, N_t. Importantly, this approach allows us to identify η such that our estimate does not depend on the level of hours per capita and firms per capita, but only on their growth rates.

To identify the parameter θ, we find the equilibrium expressions for the R&D-to-GDP ratio and profits-to-GDP ratio, and then substitute out the expression for the steady-state quality-adjusted firm size. Note that 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

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

As a result, the R&D-to-GDP ratio can be expressed as

$$\frac{\text{R\&D}_t}{\mathcal{Y}_t} = \frac{\tilde{N}_t (Z_{t+1} - Z_t)}{\mathcal{Y}_t} = \frac{\theta^2 (z_{ss} - 1)}{\left[1 - \theta^2 \left(1 + \frac{\phi}{x_t}\right)\right] x_t},$$

and solving for x_t yields

$$x_t = \frac{\theta^2}{1 - \theta^2} \left[\frac{z_{ss} - 1}{\frac{\text{R\&D}_t}{\mathcal{Y}_t}} + \phi\right]. \tag{25}$$

Equation (25) allows us to replace the latent variable of quality-adjusted firm size, x_t, in terms of the observable R&D-to-GDP ratio. Next, we find the model's expression for the profits-to-GDP ratio. In the model, we have

$$\frac{\text{Profits}_t}{\mathcal{Y}_t} = \frac{\tilde{N}_t \left(P_t X_t - X_t - \phi Z_t\right)}{\left(\frac{\mathcal{Y}_t}{Y_t}\right) Y_t} = \frac{\tilde{N}_t \left(\left(\frac{1}{\theta} - 1\right) X_t - \phi Z_t\right)}{\left(\frac{\mathcal{Y}_t}{Y_t}\right) \frac{\tilde{N}_t X_t}{\theta^2}} = \frac{\theta^2 \left[\frac{1-\theta}{\theta} x_t - \phi\right]}{\left[1 - \theta^2 \left(1 + \frac{\phi}{x_t}\right)\right] x_t},$$

where we used the pricing equation $p_t = 1/\theta$, and $\tilde{N}_t X_t = \theta^2 Y_t$ in the second equality. Substituting for x_t from (25) and solving for θ yields

$$\theta = \frac{\frac{\text{Profits}_t}{\mathcal{Y}_t} + \phi \frac{\text{R\&D}_t}{\mathcal{Y}_t} / (z_{ss} - 1)}{1 - \frac{\text{Profits}_t}{\mathcal{Y}_t}}. \tag{26}$$

Clearly, given ϕ, (26) identifies θ. 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.

We use the Euler equation for R&D investment (15) to identify the parameter α,

$$1 = \tilde{\beta}\mathbb{E}_t \left\{ \frac{c_t}{c_{t+1}} \left[\alpha \left(\frac{1-\theta}{\theta} \right) x_{t+1} + 1 \right] \right\}. \tag{27}$$

Since (27) is linear in α, substituting out x_{t+1} using (25) gives us identification for α.

To identify the parameter ν we use the Euler equation for product innovation (5). Using the free-entry condition $V_t = \nu X_t$, and the expressions for distributed dividends $D_t = (p_t - 1) X_t - \phi Z_t - I_t$, and the price equation $p_t = 1/\theta$, we can rewrite the Euler equation (5) as

$$1 = \tilde{\beta}\mathbb{E}_t \left\{ \frac{c_t}{c_{t+1}} \left[\left(\frac{1-\theta}{\theta\nu} + 1 \right) \frac{X_{t+1}/Z_{t+1}}{X_t/Z_t} - \frac{\phi + Z_{t+2}/Z_{t+1} - 1}{\nu X_t/Z_t} \right] \frac{Z_{t+1}}{Z_t} \right\}.$$

Now replacing X_t/Z_t with x_t and Z_{t+1}/Z_t with z_{ss}, we get

$$1 = \tilde{\beta}\mathbb{E}_t \left\{ \frac{c_t}{c_{t+1}} \left[\left(\frac{1-\theta}{\theta\nu} + 1 \right) \frac{x_{t+1}}{x_t} - \frac{\phi + z_{ss} - 1}{\nu x_t} \right] z_{ss} \right\}. \tag{28}$$

Since (28) is linear in ν (once multiplied though by ν), it clearly identifies ν.

To identify the parameter γ, we use the intratemporal condition for labor supply (13).

$$\gamma L_t^{\vartheta} = \frac{(1-\tau_t^l) w_t}{c_t} \quad \rightarrow \quad \gamma L_t^{\vartheta+1} = \frac{(1-\tau_t^l)(w_t L_t/\mathcal{Y}_t)}{(c_t/\mathcal{Y}_t)}. \tag{29}$$

Since the Frisch elasticity of labor supply is set to one (i.e., $\vartheta = 1$), the parameter governing the disutility of work, γ, is clearly identified from (29). In the model, γ only appears in the labor supply equation (13) and as a multiplicative term. Thus, γ only affects the level of per capita variables (e.g., L_t and N_t), and not their dynamics (e.g., when expressed in growth terms). For instance, one can express the labor-supply in growth terms and drop γ from the system of equations altogether. As a result, normalizing our data for hours-per-capita to have a sample average of one allows us to assign a numerical value to γ that is easier to interpret, without loss of generality. In equation (29), the consumption-to-GDP ratio in the denominator is constructed using the FRED series PCECA (personal consumption expenditures, billions of dollars, annual, not seasonally adjusted) and FRED series GDPA. The data for the labor share of GDP in the numerator are from the FRED series LABSHPUSA156NRUG (share of labor compensation in GDP at current national prices, annual, not seasonally adjusted). Data for the average marginal income tax rate are from Mertens and Montiel Olea (2018) and available at http://www.nber.org/data-appendix/w19171/.

The seven moment equations (22)-(24) and (26)-(29) are in terms of observable variables only and together identify the parameters in Γ. It remains to pin down the parameter for the fixed operating cost ϕ, to which we turn next.

Fixed operating cost To estimate the value of the fixed operating cost ϕ, we follow an iterative procedure, that aims at matching the impact response of TFP to an identified shock to the average marginal individual income tax rate. The IRF of TFP is estimated in the context of a SVAR framework with narratively-identified shocks.

The procedure consists of three steps:

1. Given an initial value for ϕ, say, ϕ_0, we obtain an estimate of the vector of parameters $\hat{\Gamma}(\phi_0)$, where we explicitly denote that the parameter estimates depend on the initial value ϕ_0.

2. Given ϕ_0 and the estimate of $\hat{\Gamma}(\phi_0)$, compute the IRF of TFP in the model.[6]

3. Iterate until the model-implied impact response of TFP matches the impact response of the empirical IRF.

5 Quantitative Analysis

In this section we study the quantitative predictions of the model. To this goal, we carry out two types of counterfactual experiments. In the first set of experiments, we use the model to revisit the U.S. experience of the eighties. This time period was punctuated by two important laws that legislated large cuts in marginal individual income tax rates: the Economic Recovery Tax Act (ERTA) of 1981 and the Tax Reform Act (TRA) of 1986. ERTA and TRA are commonly referred to as the "Reagan tax cuts." In the second set of experiments, we use the estimated model to make predictions about the impact of the Tax Cuts and Jobs Act (TCJA) of 2017. We evaluate the aggregate consequences of the TCJA of 2017 under alternative specifications of the future time path of tax rates.

[6] To recover an IRF for the tax rate in the model that matches that from the empirical IRF, we proceed as follows. First, we fit an AR(1) process to the actual time series of the AMIITR in the data. Second, we appropriately choose the innovations to the AR(1) process such that the realized IRF for the tax rate in the model exactly matches the empirical IRF of the AMIITR.

While both the Reagan tax cuts and the TCJA comprise provisions on several aspects of the U.S. tax code, here we focus on those pertaining to the individual income tax. In all experiments, we assume lump-sum transfers to balance the government budget on a period-by-period basis. This is mainly an operational assumption for it allows us to examine the aggregate consequences of tax reforms without taking a stand on when and how the government will balance the intertemporal budget constraint.[7] Whether this is empirically plausible is still open to debate (see, e.g., Seater, 1993, for a discussion of this issue).

5.1 External Validation of the Propagation Mechanism

In this subsection we provide external validation for the propagation mechanism of tax rate changes at work in the model. Specifically, we show that the model implications for (i) the aggregate labor supply elasticity, (ii) the responsiveness of per capita GDP growth to tax rate changes, and (iii) the IRFs of per capita hours worked, per capita number of firms, and TFP to *identified* tax rate shocks are borne out in the data.

5.1.1 Aggregate Labor Supply Elasticity

As it is well known, the Frisch elasticity of labor supply is a key object governing the responsiveness of hours worked to *temporary* changes in labor tax rates. As discussed above, we exogenously set $\vartheta = 1$ implying a Frisch elasticity of one, a value close to the lower bound of the range of estimates for aggregate hours in literature (see, e.g., Chetty et al., 2012, for a survey of existing estimates).

In addition, to compare the model-implied elasticity of aggregate hours worked to *permanent* changes in tax rates with state-of-the-art, available empirical estimates, we run regressions on artificial data from the model. More precisely, we simulate time series by feeding to the model the marginal tax rate series for the period 1950-2007, assuming that the model is along the BGP in 1950. (The ratio of government purchases to GDP is kept constant throughout at its 1950 level.)

We then run the following OLS regression on simulated per capita hours worked from the model:

$$\log(\text{hours}_t) = \alpha_0 + \alpha_1 \log(1 - \tau_t^l) + \epsilon_t, \qquad (30)$$

[7]See Ferraro and Peretto (2020) for a paper studying the implications of government debt in this class of models.

where $\tau_t^l \equiv \text{AMIITR}_t + 0.5 \times \text{AMPTR}_t$. In equation (30), the coefficient α_1 represents the elasticity of aggregate hours worked. We estimate $\hat{\alpha}_1 = 0.67$, that lines up nicely with the available estimates of the steady-state elasticity of aggregate hours (see Chetty et al., 2012; Keane and Rogerson, 2012, 2015, and references therein).

5.1.2 Real GDP per Capita

To validate the model implications for the per capita GDP growth responsiveness to income tax rate changes, we run the following OLS regressions on simulated data from the model:

$$\Delta \log \text{GDP}_{t+h} = \beta_{0,h} + \beta_{1,h}(\tau_t^l - \tau_{t-1}^l) + \eta_{t+h}, \text{ for } h = 0, 1, \dots, 5. \tag{31}$$

First, we estimate $\hat{\beta}_{1,0} = -0.69$, for the contemporaneous regression, and $\hat{\beta}_{1,1} = -0.40$, for the 1-year ahead regression. Thus, in the model, a cut in the AMTR by one percentage point raises contemporaneous per capita GDP by 0.69%, and it raises next year's per capita GDP by 0.4%.

The magnitudes of these estimated effects is comparable to existing estimates based on *identified* marginal tax rate shocks (see Barro and Redlick, 2011; Mertens and Montiel Olea, 2018). For example, Barro and Redlick run a similar estimating equation on post-war U.S. data and find that a 1 percentage point cut in the AMTR raises next year's real per capita GDP by around 0.5%. To be sure, Barro and Redlick's estimation strategy involves a careful choice of instrumental variables to address well-known endogeneity issues absent in the context here. In Mertens and Montiel Olea's work, the estimated effect is about twice that found by Barro and Redlick.

Second, the estimated coefficients $\hat{\beta}_{1,h}$ in the regressions with $h \geq 2$ are not statistically significant, suggesting that the effects of income tax rate changes die out over time, which is consistent with the large literature on the lack of growth effects of personal income tax rates (see Easterly and Rebelo, 1993; Stokey and Rebelo, 1995; Mendoza, Milesi-Ferretti and Asea, 1997; Jaimovich and Rebelo, 2017).

5.1.3 Impulse Response Functions

Here we provide novel empirical evidence about the dynamic effects of a tax rate cut on per capita hours worked, per capita number of firms, and utilization-adjusted TFP. To this goal, we estimate IRFs to a narratively-identified tax rate shock, building on a large

SVAR literature estimating the causal effects of tax policy changes. Specifically, we use a proxy-SVAR approach in which "exogenous" changes in tax liabilities are used as proxies for shocks to tax rates (see Mertens and Ravn, 2013).[8] (See Appendix B for details on data sources, variables' construction, and estimation method.)

The baseline proxy-SVAR specification includes average marginal individual income tax rate, per capita hours worked, per capita number of firms, utilization-adjusted TFP, and a set of control variables, for a sample of annual observations for the period 1977-2012. Control variables include the log of real GDP per capita, the log of the S&P index, and the federal funds rate, which allows us to capture business cycle dynamics as well as monetary policy stance. To explicitly allow for the feedback from government debt to taxes and spending, we also control for the log of real government spending per capita, the average tax rate, and the change in log real federal government debt per capita.

Figure 3 reports the empirical IRFs, and Figure 4 compares the impulse responses from the model with those estimated in the data. Two main results stand out.

First, in the data, in response to a temporary 1 percentage point tax rate cut, per capita hours worked and number of firms raise temporarily, and then sluggishly revert back to their initial level over time. The model is successful in reproducing these patterns, even though the magnitudes of the responses are somewhat smaller. We stress however that the empirical IRFs are untargeted moments. Overall, the empirical evidence supports the model predictions about the positive comovement between the labor input and number of firms. Second, in the data, TFP growth temporarily accelerates, with a peak response of nearly 0.6 percentage points. The model matches the impact response of TFP, however, the reversion to the mean is much faster in the model relative to the data.

5.2 The Reagan Tax Cuts of the Eighties

Here we ask whether and to what extent the estimated model accounts for the observed movements of key macroeconomic variables during the "Reagan tax cuts" period. To this goal, we feed to the model the *observed* U.S. tax policy and compute equilibrium paths under perfect foresights.

Reagan tax cuts experiment We assume that the economy is running along the BGP in 1980, growing at a constant 2% per year, with fiscal policy variables at their 1980 levels. At that time, the observed time paths of income and payroll tax rates for the next 28 years

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

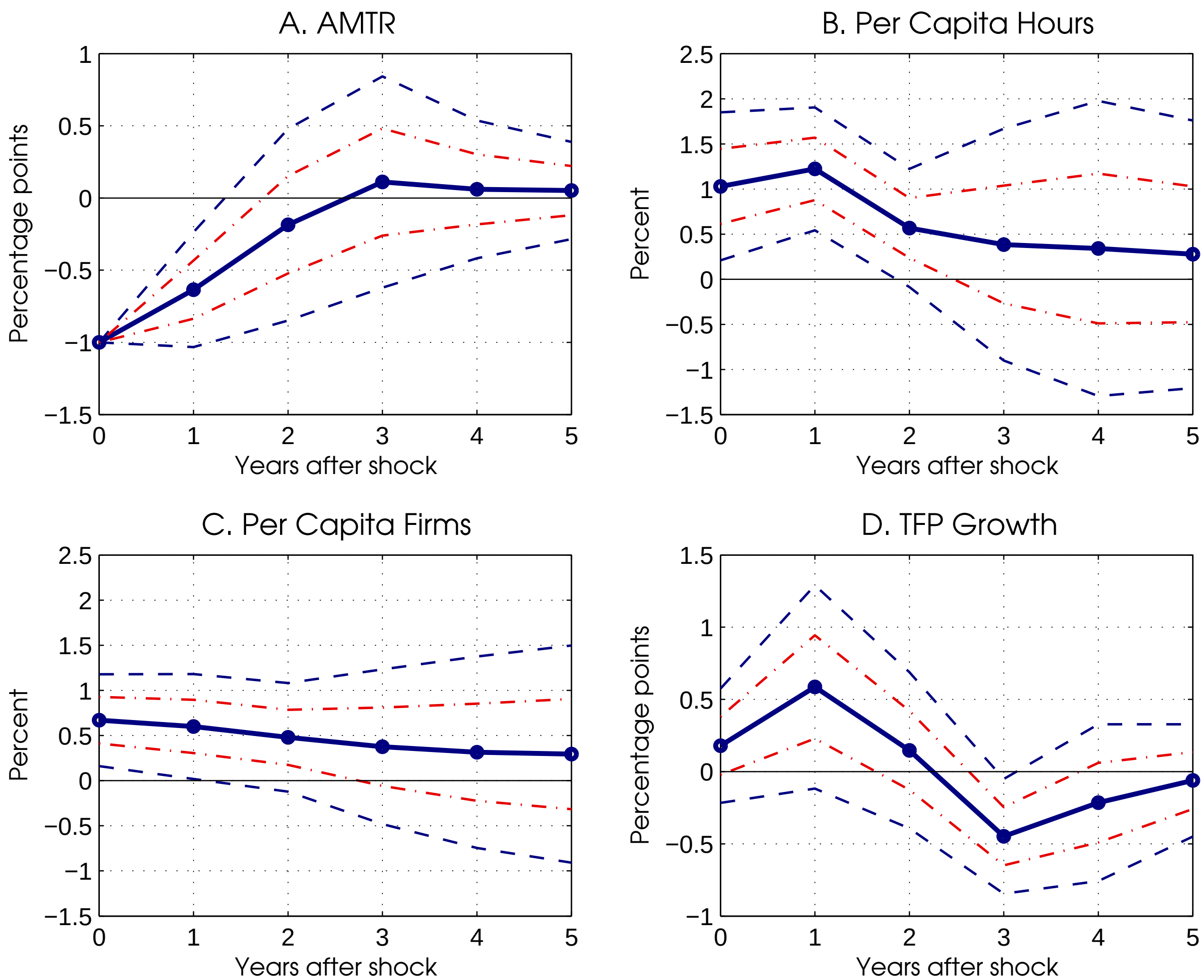

Figure 3: Empirical IRFs to a Tax Rate Cut

Notes: The figure shows the IRFs to a 1 percentage point cut in AMTR (solid lines with circles). IRFs are estimated in the context of proxy-SVARs. Dash-dotted lines are 68 percent confidence bands. Dashed lines are 95 percent confidence bands. Confidence bands are constructed with the Delta method as in Mertens and Montiel Olea (2018) with a Newey and West (1994) HAC-robust residual covariance matrix. See Appendix B for details on data sources, variables' construction, and estimation method.

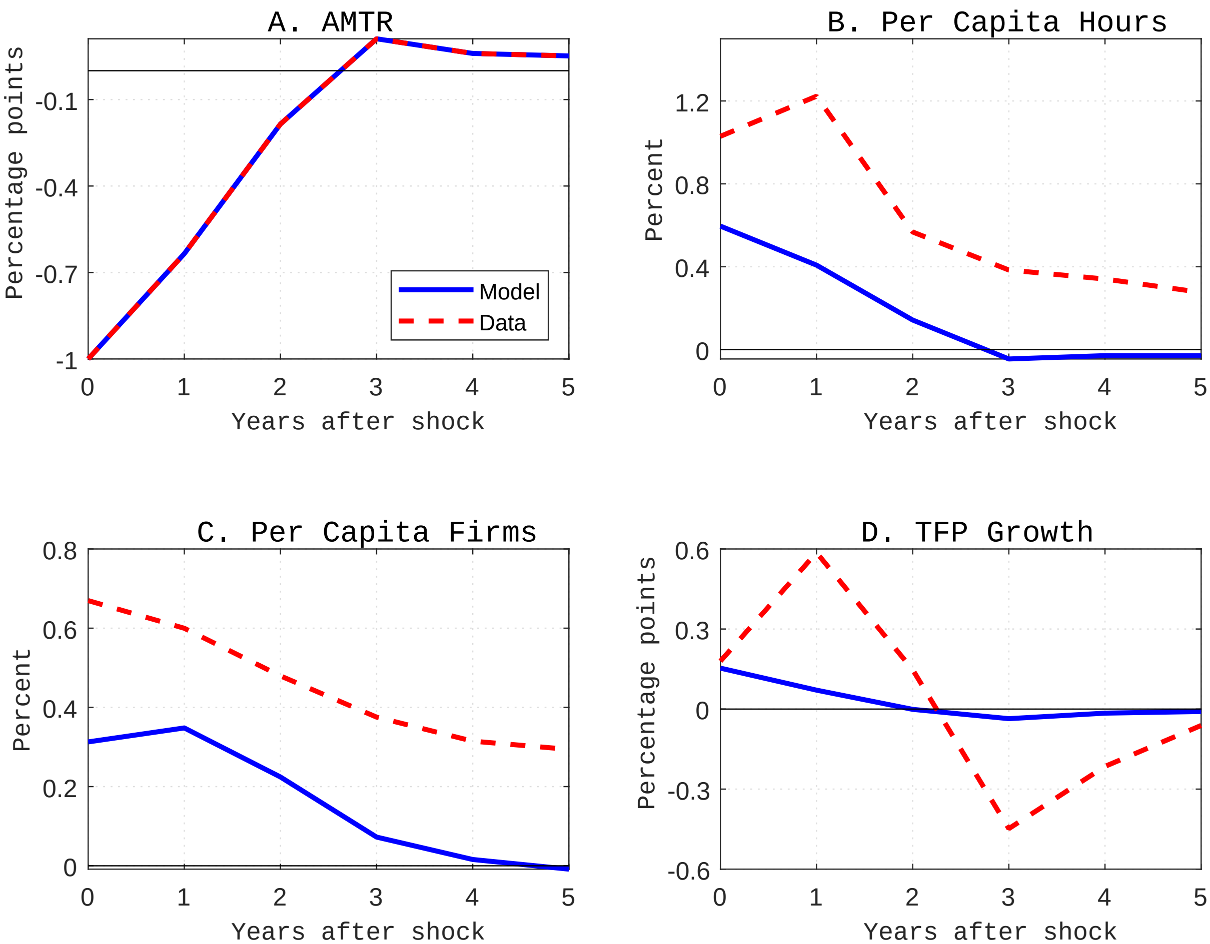

Figure 4: IRFs to a Tax Rate Cut - Model vs. Data

Notes: The figure shows IRFs in the model (solid line) and those estimated in the data in the context of a proxy-SVAR (dashed line) as reported in Figure 3. IRFs in the model are calculated as follows. We consider a stochastic version of the model in which the tax rate follows the process $\hat{\tau}^l_t = 0.886\hat{\tau}^l_{t-1} + 0.00288\epsilon^l_t$, where $\hat{\tau}^l_t$ indicates the percentage point difference between the tax rate and its unconditional mean. This is the AR(1) process that best fits the IRF of the tax rate in the data. The system starts at the steady state and the innovations ϵ^l_t, for $t = 0, ..., 5$, are set such that the realized path of the tax rate in the model exactly matches that in the data. We then find the log-linearized solution of the model and compute IRFs given the path for $\hat{\tau}^l_t$.

(1980-2007) is revealed, see panels B and C of Figure 2. (We stop in year 2007 to avoid confounding factors from the Great Recession of 2007-2009.) We assume that the tax rates remain constant at their 2007 levels from 2007 onwards. At that time, the economy starts the transition dynamics towards the new balanced growth path.

Figure 5 shows simulated time paths from the model vis-à-vis actual data, keeping government purchases as a share of GDP at its 1980 level. Importantly, the model does a good job of accounting for the observed movements in TFP, average labor productivity (ALP), market hours worked and firms per capita from 1980 to 1990. We view this as a successful test of the theory. This exercise confirms that the magnitude of the responses of endogenous variables to the observed changes in income and payroll tax rates is in fact empirically plausible. (See also Figure 6 for the experiment where only the individual marginal income tax rate varies over time, whereas the payroll tax rate is kept fixed.)

Role of the payroll tax rate Figure 7 shows the results of a counterfactual experiment in which the only source of variation are the actual movements in AMPTR. AMIITR and government purchases-to-GDP ratio are kept constant at their 1980 levels. Two striking patterns stand out. First, TFP and labor productivity growth barely move, suggesting that payroll tax rates alone cannot account for the large swings in growth rates observed over this period. Second, market hours worked and firms per capita fall, which is at odds with the data. This happens because the AMPTR has steadily risen during the eighties, leveling off in the early-90s, see panel C of Figure 2.

Role of the government purchases-to-GDP ratio Figure 8 shows the results of the counterfactual experiment in which we shut down the observed movements in tax rates and let the government spending-to-GDP ratio vary in the model as in the data. The results are clear-cut. During the 80s, government spending played no role in determining observed aggregate outcomes. This happens because government purchases as a share of GDP have been stable over the period, see panel D of Figure 2.

5.3 The Tax Cuts and Jobs Act of 2017

Having established that the model accounts well for the U.S. experience of the eighties, we now conduct counterfactual experiments aimed at quantifying the impact of the Tax Cuts and Jobs Act (TCJA) of 2017. Notably, we focus on the provisions in TCJA pertaining to individual income tax rates. To proceed, we need to specify the projected time path of

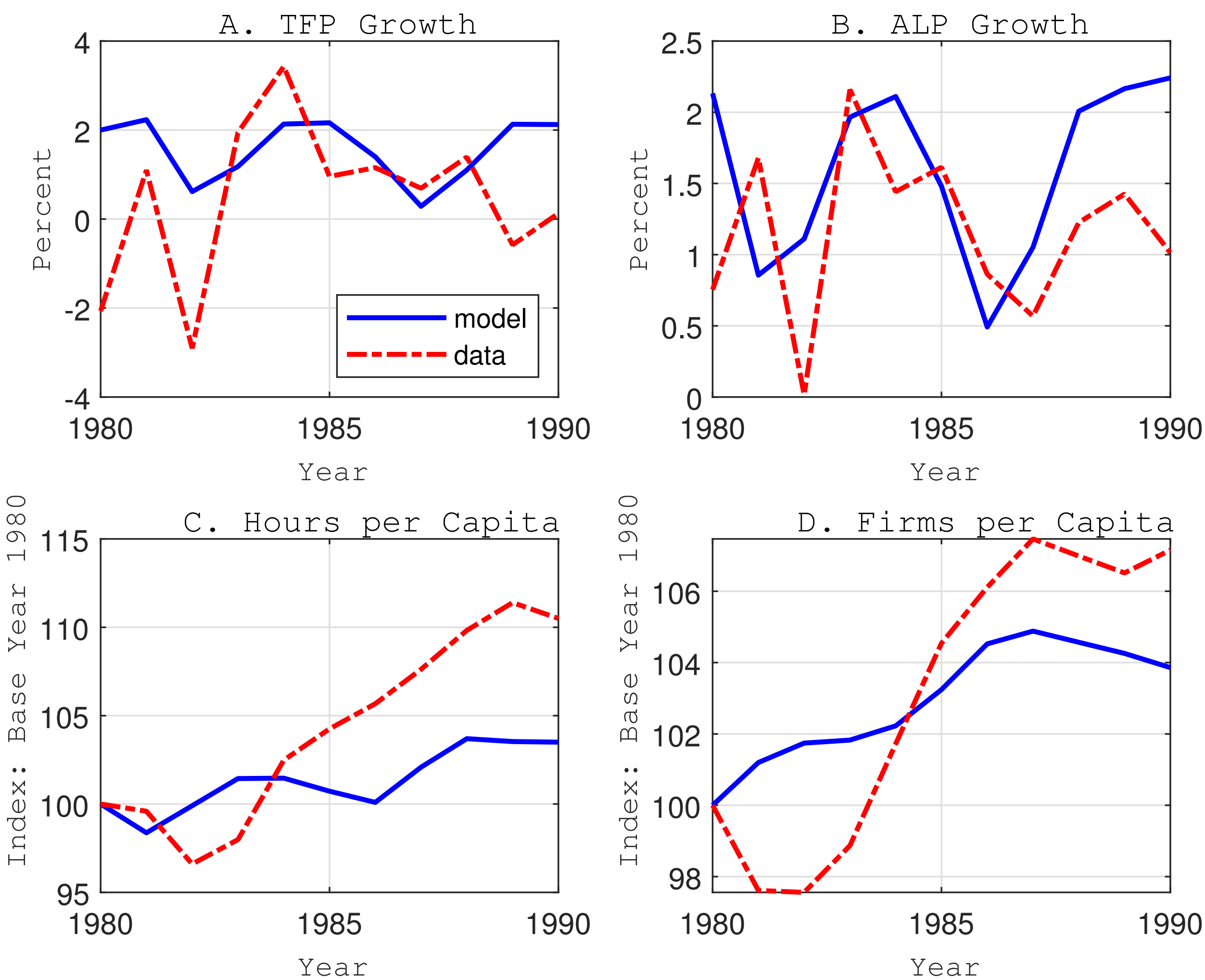

Figure 5: The Reagan Tax Cuts - Individual Income and Payroll Tax Rates

Notes: Model simulated paths are calculated by feeding to the model the observed series of AMIITR and AMPTR, see panels B and C of Figure 2. In all panels, the government purchases-to-GDP ratio is kept constant at its 1980 level. Lump-sum transfers adjust to balance the government budget on a period-by-period basis.

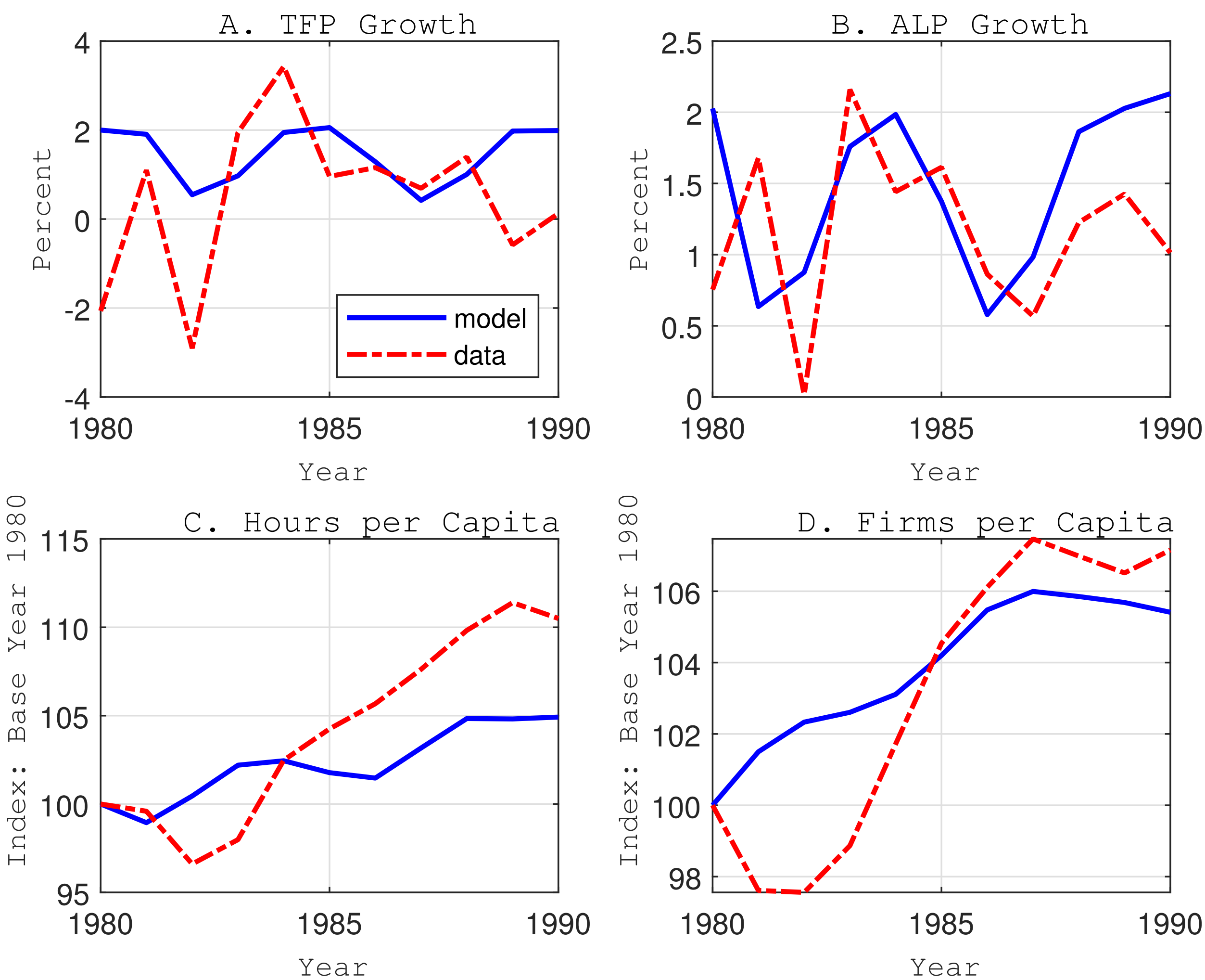

Figure 6: The Reagan Tax Cuts - Individual Income Tax Rate

Notes: Model simulated paths are calculated by feeding to the model the observed series of AMIITR, see panel B of Figure 2. In all panels, AMPTR and the government purchases-to-GDP ratio are kept constant at their 1980 levels. Lump-sum transfers adjust to balance the government budget on a period-by-period basis.

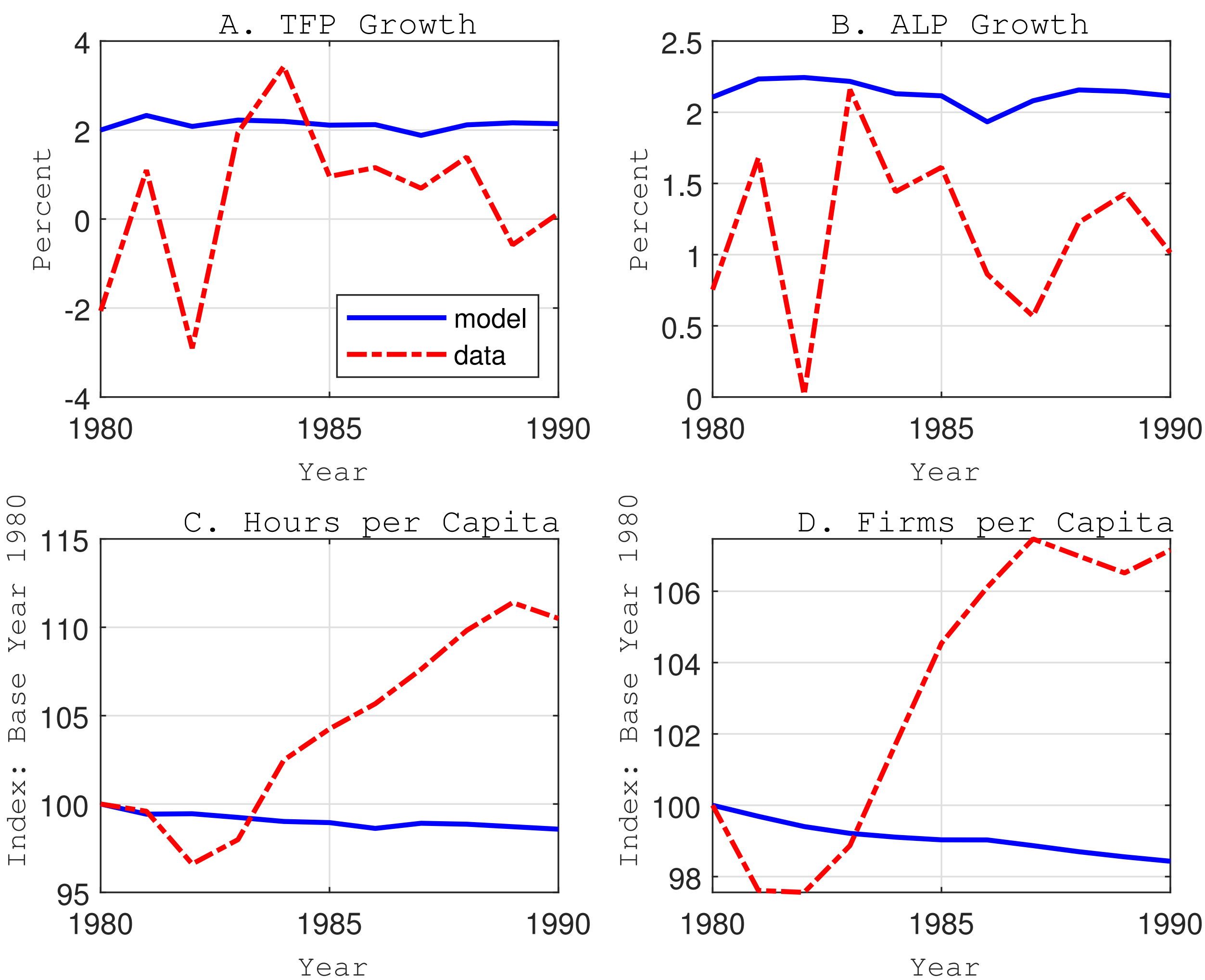

Figure 7: The Reagan Tax Cuts - Payroll Tax Rate

Notes: Model simulated paths are calculated by feeding to the model the observed series of AMPTR, see panel C of Figure 2. In all panels, AMIITR and the government purchases-to-GDP ratio are kept constant at their 1980 levels. Lump-sum transfers adjust to balance the government budget on a period-by-period basis.

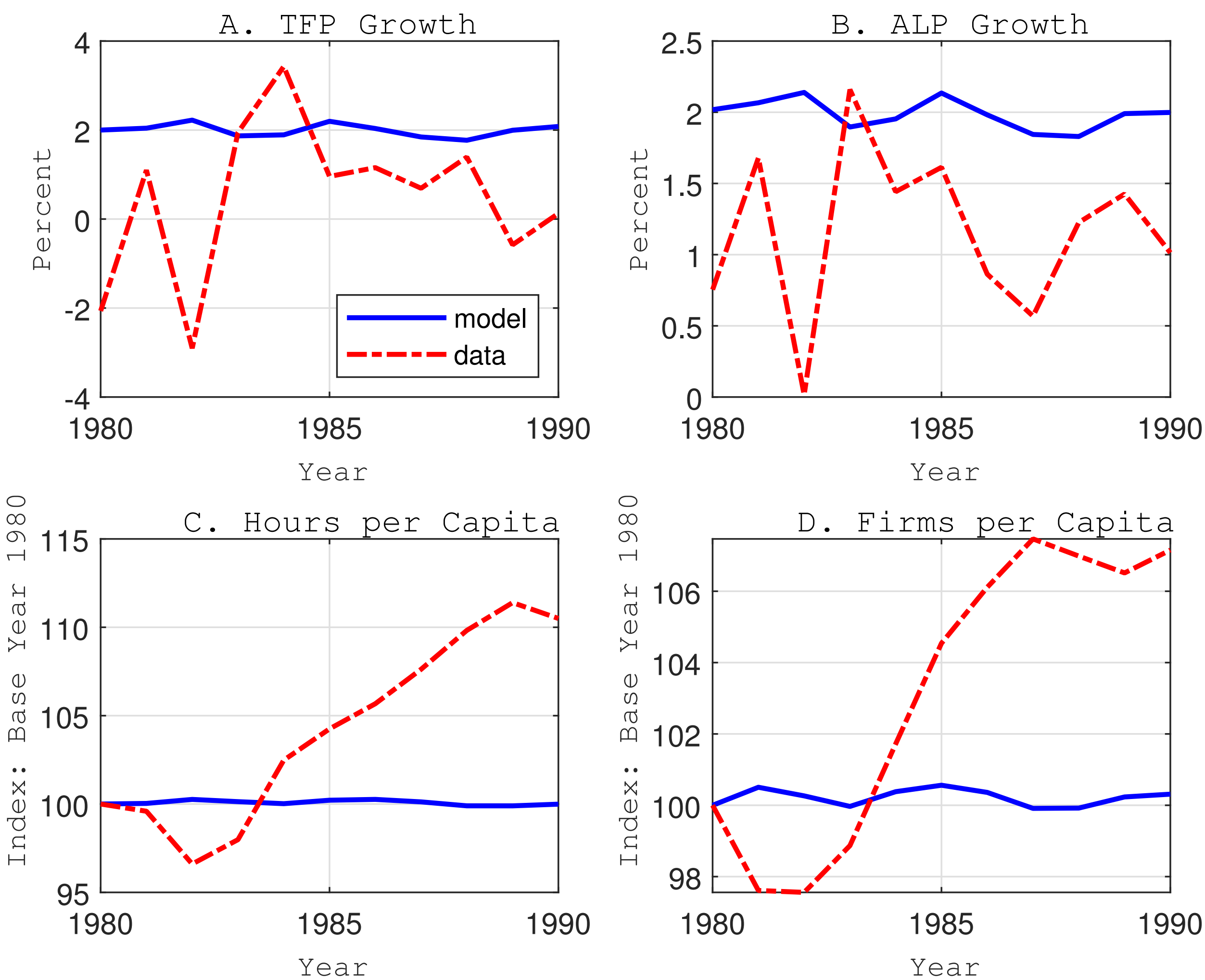

Figure 8: The Reagan Tax Cuts - Government Purchases-to-GDP Ratio

Notes: Model simulated time paths are calculated by feeding to the model the observed series of government purchases-to-GDP ratios, see panel D of Figure 2. In all panels, AMIITR and AMPTR are kept constant at their 1980 levels. Lump-sum transfers adjust to balance the government budget on a period-by-period basis.

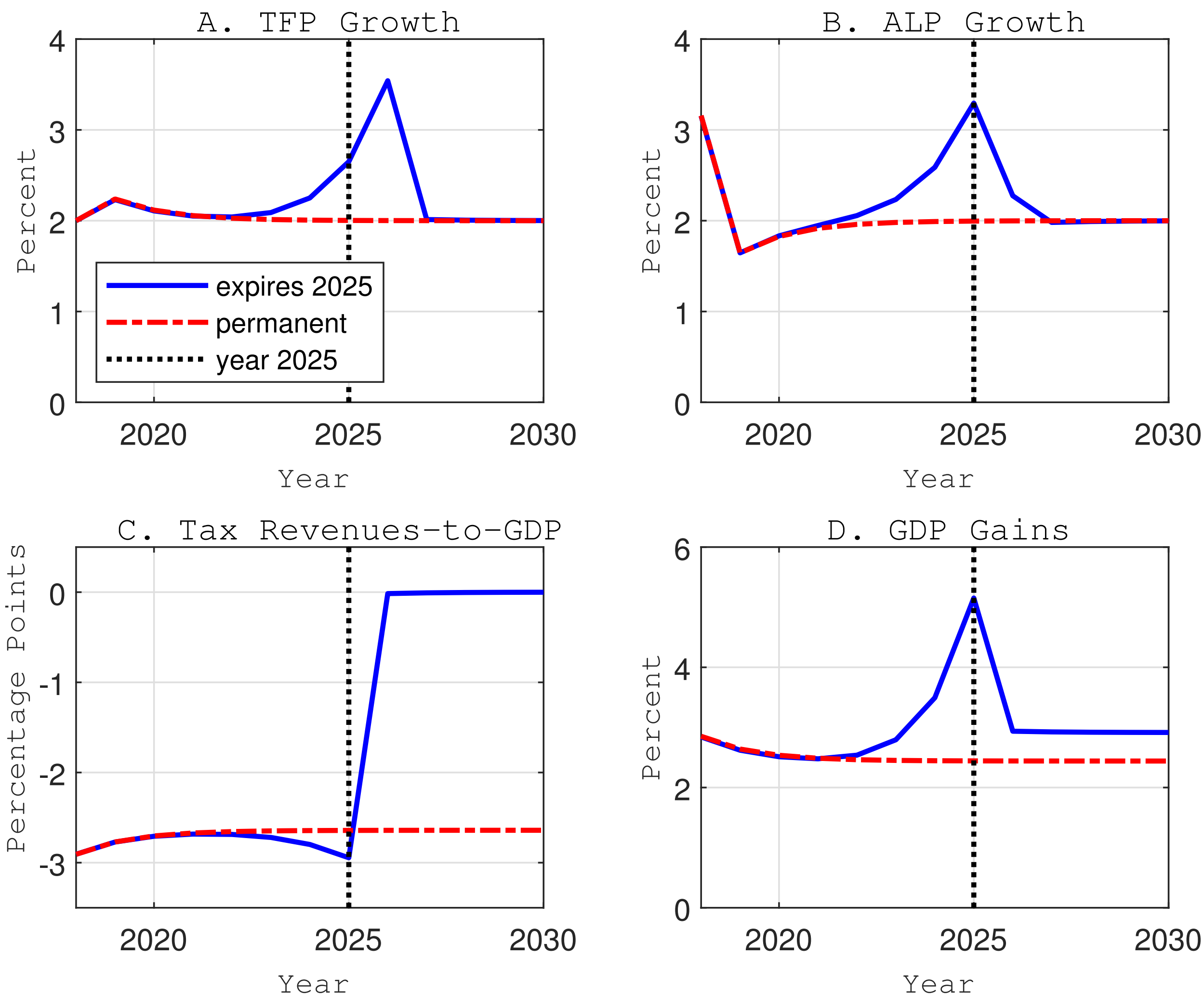

Figure 9: The TCJA of 2017 Experiment

Notes: Solid lines show equilibrium time paths simulated from the model under a temporary 3 p.p. tax rate cut, that is set to expire in year 2025, as in the TCJA of 2017. The model economy is assumed to be on the BGP in year 2017 with an AMIITR of 26%. AMIITR equals 23% from year 2018 to 2025 and it returns to 26% from 2026 onwards. Dashed lines show time paths under a permanent 3 p.p. tax rate cut, where we feed to the model an AMIITR of 23% from year 2018 onwards. In all panels, AMPTR and the government purchases-to-GDP ratio are kept constant at their 2017 levels. Lump-sum transfers adjust to balance the government budget on a period-by-period basis.

tax rates implied by the TCJA and the private sector expectations about that path. Next, we describe in detail how we specify these model inputs.

Projected tax rates under TCJA In terms of implied changes in individual marginal income tax rates, available estimates point to a major change in tax incentives from TCJA. Mertens (2018) calculates that TCJA reduces AMTR by 2.75 percentage points. According to calculations by the Tax Policy Center, TCJA would reduce AMTR on wages and salaries by 3.2 percentage points.[9] 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.

TCJA experiment Here, we use the model to quantify the aggregate impact of TCJA. We proceed in two steps. First, we assume that the economy is on the BGP in 2017, with the following fiscal policy: $\tau^l_{2017} = 26\%$, $\tau^f_{2017} = 4\%$, and $g_{2017} = 20\%$. Second, in 2017, the new future path of tax rates is announced, so that the private sector has perfect foresights about the announced path. We consider a 3 percentage point cut in AMIITR, that is the mid-point of the available estimates. Further, 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 $\tau^l_t = 23\%$ for $2018 \leq t \leq 2025$ and $\tau^l_t = 26\%$ for all $t \geq 2026$.

Figure 9 shows equilibrium time paths simulated from the model. In response to the temporary tax rate cut, the economy experiences a productivity growth acceleration, with a peak response occurring near the 2025 expiration date. The temporary output growth acceleration translates into a permanent gain in per capita output, relative to the BGP before the tax rate cut. The model predicts per capita GDP to be 5 percent higher than the level that would have prevailed in the counterfactual without TCJA by year 2025.

Permanent vs. temporary tax changes A natural question to ask 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 2.5 percent permanent increase in per capita GDP by year 2025. Under a permanent tax rate cut, the variability

[9] Preliminary calculations from the Tax Policy Center are available at https://www.taxpolicycenter.org/model-estimates/conference-agreement-tax-cuts-and-jobs-act-dec-2017/t17-0323-effective-marginal.

of growth rates is much reduced compared to the experiment featuring a temporary tax rate cut, pointing to the importance of intertemporal substitution.

6 Conclusion

We develop, estimate, and provide empirical validation for a quantitative Schumpeterian model of growth. Prominent feature of the theory is the equilibrium interaction between product and quality innovation: entrant firms create new products whereas incumbents improve own existing products. The model estimated to match key moments of U.S. data, accounts reasonably well for the observed movements in TFP, labor productivity, market hours worked and number of firms per capita during the Reagan tax cuts of the eighties. We use the model to evaluate the provisions of the Tax Cuts and Jobs Act (TCJA) of 2017 that pertain to the individual income tax. We find that a 3 percentage points cut in the average marginal individual income tax rate, set to expire in 2025 as in TCJA, raises real GDP per capita by 5 percent in year 2025.

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

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A Appendix: Model

In this appendix we detail the derivations of the equations presented in the main text of the paper. We then discuss the mapping of the model to NIPA.

A.1 Equilibrium conditions

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

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

$$Y_t = \theta^{\frac{2\theta}{1-\theta}} \tilde{N}_t^{1-\eta} Z_t L_t, \tag{A.2}$$

$$\gamma L_t^{\vartheta} C_t = (1 - \tau_t^l) w_t, \tag{A.3}$$

$$V_t = \mathbb{E}_t \left[\tilde{M}_{t,t+1} \left(D_{t+1} + V_{t+1}\right)\right], \tag{A.4}$$

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

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

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

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

$$1 = \mathbb{E}_t \left\{ \tilde{M}_{t,t+1} \left[\left(\frac{1-\theta}{\theta}\right) \frac{\alpha X_{t+1}}{Z_{t+1}} + 1 \right] \right\}, \tag{A.9}$$

$$F_t = \left(\frac{1-\theta}{\theta}\right) \theta^{\frac{2}{1-\theta}} \left(\frac{L_t}{\tilde{N}_t^{\eta}}\right) Z_t - \phi Z_t, \tag{A.10}$$

$$D_t = F_t - I_t, \tag{A.11}$$

$$G_t + \Omega_t = T_t, \tag{A.12}$$

$$G_t = g\left(Y_t - \tilde{N}_t X_t - \phi \tilde{N}_t Z_t\right), \tag{A.13}$$

$$T_t = \left(\tau_t^l + \tau_t^f\right) w_t L_t. \tag{A.14}$$

A.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_{t+1}^a) space, where $i_t \equiv I_t / Z_t$ is the current R&D investment rate and r_{t+1}^a is the rate of return to corporate equity one period ahead.

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

$$r^a_{t+1} = \left(\frac{1-\theta}{\theta}\right) \alpha x_{t+1}. \tag{A.15}$$

Rate of return to entrants' investment (RRE) The expression in (A.4) yields the rate of return to corporate equity in symmetric equilibrium:

$$r^a_{t+1} = \frac{D_{t+1}}{V_t} + \frac{V_{t+1} - V_t}{V_t}. \tag{A.16}$$

Next, using the expression for dividends $D_t = F_t - I_t$ in (A.11), it yields:

$$r^a_{t+1} = \frac{F_{t+1} - I_{t+1}}{V_t} + \frac{V_{t+1} - V_t}{V_t}. \tag{A.17}$$

Using the free-entry condition $V_t = \nu X_t$ in (A.8), and multiplying and dividing by Z_t the first two terms on the right-hand side of (A.17), it yields:

$$r^a_{t+1} = \frac{F_{t+1}/Z_t - I_{t+1}/Z_t}{\nu X_t/Z_t} + \frac{X_{t+1}/Z_t - X_t/Z_t}{X_t/Z_t}. \tag{A.18}$$

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:

$$r^a_{t+1} = \left[\frac{\left(\frac{1-\theta}{\theta}\right) x_{t+1} - \phi - i_{t+1}}{\nu x_t}\right] (1 + i_t) + \frac{x_{t+1}(1 + i_t)}{x_t} - 1. \tag{A.19}$$

We refer to the expression in equation (A.19) as the entrants' investment schedule (RRE schedule).

A.3 Production innovation and quality innovation locus

Here we provide details on the derivation of the product (PI) and quality innovation (QI) locus. The PI and QI locus 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, equation (A.15) reduces to

$$R^a = \left(\frac{1-\theta}{\theta}\right)\alpha x + 1. \tag{A.20}$$

Next, using the expression for the effective SDF, and realizing 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:

$$z = \beta(1-\delta)\left[\left(\frac{1-\theta}{\theta}\right)\alpha x + 1\right]. \tag{A.21}$$

Next, in the steady state, equation (A.19) reduces to

$$R^a = \left[\left(\frac{1-\theta}{\nu\theta}\right) - \frac{\phi + i}{\nu x}\right](1+i) + 1 + i. \tag{A.22}$$

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

$$1 = \beta(1-\delta)\left(1 + \frac{1-\theta}{\nu\theta} - \frac{\phi + z - 1}{\nu x}\right). \tag{A.23}$$

A.4 Model income and product accounts (MIPA)

Here we provide details on the calculation of gross domestic product (GDP) in the model in relation to the U.S. national income and product accounts (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.

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 $\text{VA}_t^{\text{FS}} = Y_t - p_t \tilde{N}_t X_t$, 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 numeraire, whose price is then normalized to one.) Value-added in the corporate sector is $\text{VA}_t^{\text{CS}} = p_t \tilde{N}_t X_t - \tilde{N}_t X_t - \phi Z_t$, 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, $\text{GDP}_t = \text{VA}_t^{\text{FS}} + \text{VA}_t^{\text{CS}} = Y_t - \tilde{N}_t X_t - \phi Z_t$.

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*, (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, $\text{GDP}_t = C_t + G_t + \tilde{N}_t I_t + \nu X_t \Delta_t^N$, 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.

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, $\text{GDI}_t \equiv \text{GDP}_t = Y_t - \tilde{N}_t X_t - \phi Z_t$.

B Appendix: Empirics

In this appendix, we describe data sources, variables' construction, and the details of the procedure used to estimate IRFs in the context of structural vector autoregressions (SVARs) with narrative identification. Specifically, we use a proxy-SVAR approach in which "exogenous" changes in tax liabilities are used as proxies for shocks to tax rates (see Mertens and Ravn, 2013). We refer the reader to Ramey (2016) for a review article of the SVARs literature on the effects of tax changes.

Average marginal tax rate (AMTR) To construct AMTR, we follow Barro and Redlick (2011) and consider a notion of "labor income" that includes wages, self-employment, partnership, S-corporation income. The data are taken from the CPS March Supplement. AMTR is the sum of the federal individual income tax and the payroll (FICA) tax. We use the NBER-TAXSIM program to simulate marginal income tax rates and marginal payroll tax rates at the individual level. We then construct AMTR as the sum of average marginal individual income tax rate (AMIITR) and average marginal payroll tax rate (AMPTR), using adjusted gross income (AGI) shares as weights.

Identification of tax shocks Tax shocks are identified in the context of SVARs using proxies for exogenous variation in tax rates as external instruments (Mertens and Ravn, 2013). We use the proxies constructed in Ferraro and Fiori (2020) for exogenous changes in AMTRs. To select instances of exogenous variation in tax rates, Ferraro and Fiori (2020) follow the narrative approach proposed by Romer and Romer (2010): changes in total tax liabilities are classified as "exogenous" based on the motivation for the legislative action being either long-run considerations, that are unrelated to the business cycle, or inherited budget deficits.

To account for potential "anticipation effects," only individual income tax liability changes legislated and implemented within the year are included, this approach is in line with Mertens and Montiel Olea (2018). According to this criterion, seven tax reforms are identified as exogenous: (1) Revenue Act of 1964; (2) Revenue Act of 1978; (3) Economic Recovery Tax Act 1981; (4) Tax Reform Act of 1986; (5) Omnibus Budget Reconciliation Act of 1990; (6) Omnibus Budget Reconciliation Act of 1993; (7) Jobs and Growth Tax Relief Reconciliation Act of 2003.

The impact of a reform is measured as the difference between two counterfactual tax rates. The first counterfactual tax rate is calculated 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 $t-1$ statutory tax rates and brackets. The difference between the two isolates then the impact that a tax reform implemented in year t had on the AMTR. An issue that arises with these type of calculations is the indexing of the federal tax system starting in 1985. To address this concern, we rescale incomes by the automatic adjustments in bracket widths embedded in the federal tax code.

SVAR specification The baseline reduced-form VAR specification includes the average marginal individual income tax rate, per capita hours worked, per capita number of firms, utilization-adjusted total factor productivity (TFP), and a set of control variables for the sample of annual observations for the period 1977-2012. Control variables include the log of real GDP per capita, the log of the S&P index, and the federal funds rate, which allows us to capture business cycle dynamics, the monetary policy stance, as well as the effects of bracket creep. To explicitly allow for the feedback from debt to taxes and spending, the log of real government spending per capita (purchases and net transfers), the average tax rate and the change in log real federal government debt per capita are included, too.