OPTIMAL FISCAL POLICY IN A SCHUMPETERIAN MODEL

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SUMMARY

Fiscal policy has received much attention in the literature on taxation and growth. Numerous theoretical and empirical studies have been devoted to understanding the growth and welfare effects of various taxes and government expenditures and the optimal structure of tax systems (e.g., Chamley, 1986; Barro, 1990; Turnovsky, 1996; Judd, 1997; Guo and Lansing, 1999; and Turnovsky, 2000). Almost all the theoretical studies in this literature use either neoclassical models or capital-based endogenous growth models. The majority of these studies show two typical results for optimal tax structure: first, consumption and leisure are uniformly taxed; second, the steady-state optimal tax on physical capital income is zero or negative, depending on the market structure.

However, these papers give little specific implication for technology-leading economies. In particular, they do not address the questions raised in this thesis: i) is it possible for the fiscal policy based on consumption taxation, income taxation and government expenditures to attain social optimum in technology-leading economies; (ii)if not, what supplemental instruments are needed; (iii) what are the characteristics of the optimal fiscal policy for technology-leading economies. It is an outstanding fact of technology-leading economies that economic growth is mainly driven by innovations. Since capital-based models do not capture this feature, they cannot appropriately characterize technology-leading economies. As a result, conclusions based on these models may not hold true for technology-leading economies.

In this thesis, we investigate optimal fiscal policy in a Schumpeterian model of Howitt and Aghion (1998) that characterizes technology-leading economies. We extend the original model by endogenizing the labor supply so that optimal fiscal policy can be studied in a richer set-up. We find that government's interventions on R&D

activities (using R&D subsidies or taxes) may be necessary for replicating the first-best outcome in technology-leading economies. Under plausible parameterization, however, R&D subsidies are indispensable. Specifically, when the spillover effect is very small or the monopoly power is very strong, R&D subsidies are needed to reduce the marginal cost of R&D. This finding is new to our knowledge. It is also consistent with the observation in the real world that governments usually adopt R&D subsidies to promote innovation.

In addition, capital investment subsidies are required to help achieve first-best level of investment and they have to be larger than capital income taxes. The magnitudes of capital investment subsidies depend positively upon the degree of monopoly power. The intuition is that capital investment subsidies serve to correct the distortions in investment caused by monopoly and capital income taxes.

Finally, first-best policy also requires consumption and leisure be taxed uniformly, which is a well-known result in the literature.

The existence of first-best policy relies on the magnitudes of spillover effect and R&D productivity parameter, for which the empirical evidence is not available. In such a case, we then focus on numerical analysis. Simulation results reveal that both capital investment subsidies and R&D subsidies can help increase welfare even when the first-best policy is not available.

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1. Introduction

Fiscal policy has received much attention in the literature on taxation and growth. Numerous theoretical and empirical studies have been devoted to understanding the growth and welfare effects of various taxes and government expenditures and the optimal structure of tax systems (e.g., Chamley, 1986; Barro, 1990; Turnovsky, 1996; Judd, 1997; Guo and Lansing, 1999, Turnovsky, 2000). Almost all the theoretical studies in this literature use either neoclassical models or capital-based endogenous growth models.[1] The majority of these studies show two typical results for optimal tax structure: first, consumption and leisure are uniformly taxed; second, the steady-state optimal tax on physical capital income is zero or negative, depending on the market structure.

However, these papers give little specific implication for technology-leading economies. In particular, they do not address the questions raised in this thesis: (i) is it possible for the fiscal policy based on consumption taxation, income taxation and government expenditures to attain social optimum in technology-leading economies; (ii)if not, what supplemental instruments should be included; (iii) what are the characteristics of the optimal fiscal policy for technology-leading economies. It is an outstanding fact of technology-leading economies that economic growth is mainly driven by innovations. Since capital-based models do not capture this feature, they cannot appropriately characterize technology-leading economies. As a result, conclusions based on these models may not hold for technology-leading economies.

Within a Schumpeterian framework, Howitt and Aghion (1998) shed a light for further research on fiscal policy. They introduce capital investment subsidy and R&D subsidy to examine the effects of government's intervention on economic growth. In this thesis, we extend Howitt and Aghion (1998) by considering an important factor

[1] Zeng and Zhang (2002) study the long-run growth effects of consumption taxes and income taxes in a non-scale R&D growth model with endogenous saving and labor-leisure choices.

that has been used in the literature on taxation and growth: the trade-off between labor and leisure. This extension allows us to study optimal fiscal policy in a richer set-up. We find that in technology-leading economies the government's interventions on R&D activities (using R&D subsidies/taxes) may be necessary for producing first-best outcome. Under plausible parameterization, however, R&D subsidies are indeed indispensable. In particular, when the spillover effect is very small or monopoly power is very strong, R&D subsidies are needed to reduce the marginal cost of R&D so as to encourage R&D investment. This finding is consistent with the observation in the real world that governments usually adopt R&D subsidies to promote innovation.

Notably, a firm with a monopoly has more incentive to invest in R&D that will protect its monopoly than does a new entrant that would become its competitor. Monopoly firms are usually giants that have plenty of resources and more specific knowledge of their industries. Thus, they are more likely to succeed in R&D race. It then follows that R&D sector is in general dominated by monopoly firms. Furthermore, these firms tend to block technology diffusion in order to protect their monopoly. For those reasons, R&D sector demonstrates strong monopoly power and small spillover effect. R&D subsidies are thus justified in the real world.

In addition, investment subsidies (we use this term to refer to capital investment subsidies) are required to help achieve ideal level of investment and it has to be larger than capital income tax. The magnitude of investment subsidies depend positively on the degree of monopoly power. In the presence of monopoly power, investment allocation is always sub-optimal. Accordingly, investment subsidies become necessary to stimulate capital investment.

Finally, in agreement with the previous work, the first-best tax structure requires that consumption and leisure be taxed uniformly.

The remainder of this thesis is organized as follows. Chapter 2 reviews the existing literature. Chapter 3 describes the economic environment and introduces the basic framework. Chapter 4 provides the analytical results. It characterizes the decentralized equilibrium and gives solutions for the social planner's problem. Chapter 5 describes the optimal fiscal policy and provides numerical results. Finally, some concluding remarks are given in chapter 6. All the proofs and derivations are relegated to the appendices.

2. Literature Review

One of the most interesting and relevant topics in public finance concerns the optimal choice of tax rates. This question has a long history in economics beginning with the seminal work of Ramsey (1927). In that paper, Ramsey characterizes the optimal levels for a system of excise taxes on consumption goods. He assumes that the government's goal is to choose these taxes to maximize social welfare subject to the constraints it faces. These constraints are assumed to be of two types. First, a given amount of revenues is to be raised. Second, Ramsey understands that whatever tax system the government adopts, consumers and firms in the economy would react in their own interest through a system of (assumed competitive) markets. This observation gives rise to a second type of constraint on the behavior of the government-it must take into account the equilibrium reactions by firms and consumers to the chosen tax policies. Ramsey's insights have been developed extensively in the last two decades.

Chamley (1986) analyzes the optimal tax on capital income using a standard neoclassical growth model in which the government sets the level of its expenditures exogenously. The population is heterogeneous. Agents have infinite lives and utility functions which are extensions from the Koopmans form. Chamley (1986) asserts that when the consumption decisions in a given period have only negligible effect on the structure of preferences for periods in the distant future, then the second-best tax rate on capital income converges to zero in the long run. The Chamley analysis do not consider any externalities from government expenditure.

In a simple model of endogenous growth, Barro (1990) considers tax-financed government services that affect production or utility and finds that the decentralized choices of growth and saving are too low. Barro (1990) claims that taxes on wages and consumption have no effect; they operate like lump-sum taxes.

The framework of Turnovsky (1996) differs from Chamley (1986) in the following important respect. By specifying government expenditure as a fraction of output, its level is no longer exogenous, but instead is proportional to the size of the growing capital stock. The decision to accumulate capital stock by the private sector leads to an increase in the supply of public goods in the future. If the private sector treats government spending as independent of its investment decision, government expenditure may generate an externality that requires a tax on capital to correct.

Judd (1997) augments the standard growth model to allow for imperfectly competitive product markets. He shows that the steady-state optimal tax on capital income can be negative. The basic idea is that the government can use tax policy as a substitute for antitrust policy. In particular, a subsidy to capital income can help to overcome the classic inefficiency of a monopoly that yields lower long-run levels of capital and output in comparison to a perfectly competitive economy.

Guo and Lansing (1999) extend the analysis of Judd (1997) by allowing for depreciation of physical capital, a depreciation tax allowance and endogenous government expenditures. They disaggregate the government's investment policy into two separate components: a capital tax and a depreciation allowance. Their analysis show that the steady-state optimal tax on capital income can be negative, positive or zero, depending crucially upon (i) the degree of monopoly power, (ii) the extent to which monopoly profits can be taxed, (iii) the size of the depreciation allowance and (iv) the magnitude of government expenditures.

Judd (1999) finds that the optimal long-run tax on capital income is zero even if the capital stock does not converge to a steady state nor to a steady-state growth rate. The key assumptions of Judd (1999) are competitive factor markets, a flexible set of tax policy instruments and the presence of some public goods. According to Judd (1999), the nature of the optimal tax system in representative agent models do not depend on the presence of stability of Turnovsky (1996).

Turnovsky (2000) introduces an elastic labor supply determined by the labor-leisure tradeoff of agents. The endogeneity of labor supply causes both the consumption and labor income tax to have adverse effects on the growth rate, as does the tax on capital income. Due to its adverse wealth effect, a lump-sum tax financed increase in government consumption expenditure in the decentralized economy has a positive effect on the growth rate. This positive effect on the growth rate contrasts with the negative effect in the centrally planned economy. Turnovsky (2000) asserts that in general the optimal tax rates will depend upon the chosen aggregate level of government expenditures relative to the optimum. If government expenditures are chosen optimally, the optimal tax rate on capital income is zero and leisure and consumption should be taxed uniformly.

The literature has so far focused on capital-based models. It is interesting to further explore the issue of optimal fiscal policy in a model with innovation. Our model is based on Howitt and Aghion (1998) who argue that physical capital accumulation and innovation are determinants of long-run growth.

Based on the neoclassical growth theory represented by Solow-Swan model, most economists agree that although both capital accumulation and technological progress contribute to economic growth, only technological progress plays a vital role in the long-run. Capital accumulation only affects the level of output but not the growth rate. For example, Romer(1990), Grossman and Helpman (1991), and Blanchard (1997) assert that the incentive for innovation determines the rate of technological progress, which in turn determines the long-run growth rate, independent of the amount of physical capital. In contrast, Howitt and Aghion (1998) argue that physical capital accumulation and technological progress are in general complementary and both of them play critical roles in long-run economic growth. The intuition is that R&D requires a great deal of physical capital in the forms of buildings, computers, laboratories and other research facilities. Thus, physical capital is a significant input to R&D and a subsidy to capital accumulation will increase R&D intensity and in turn enhance economic growth.

Howitt and Aghion (1998) examine economic growth through the channel of obsolescence (or the improvement of product quality) that has received little attention in the literature on endogenous growth. The economic intuition behind the obsolescence is that improved version of products render the previous ones out-of-fashion. In Howitt and Aghion (1998), the arrival of innovation is governed by a Poisson distribution. The amount of research in any period depends negatively on the expected amount of research in the next period. The reason is that successful R&D brings new technology and destroys the profits of previous innovation. Since the profits from innovation are temporary, the expectation of more research in the next period will discourage R&D activities in the current period.

Howitt and Aghion (1998) also provide some perspectives for further research on fiscal policy. They introduce two elements into the model: capital investment subsidy and R&D subsidy to examine the effects of government's intervention on economic growth. They show that growth rate depends positively on the two subsidy rates and the size of innovations but negatively on the elasticity of marginal utility, the rate of time preference and the rate of depreciation. They indicate that an increase in the subsidy rate on capital investment will enhance R&D intensity by raising capital accumulation, which in turn contribute to the long-run growth. However, contrary to the argument of neoclassical growth theory and other endogenous growth theories, a subsidy on capital accumulation, either physical or human capital, will have a permanent effect on growth rate. The policy implication of their result is that investment subsidy may be as effective as R&D subsidy to stimulate growth. Therefore, government may choose to subsidize capital investment to help growth since it is difficult to subsidize R&D directly and practically.

In this thesis, we extend the model of Howitt and Aghion (1998) by endogenizing labor supply to investigate optimal fiscal policy. Capturing the essential aspects of technology-leading economies, this extension is useful in providing policy implications.

3. The Model

The basic framework is due to Howitt and Aghion (1998). We extend the model by considering the trade-off between labor and leisure. We consider a closed economy populated with L_t identical infinitely-lived individuals at time t. Assume that population is constant over time ($L_t = L$, $\forall t$). The representative agent is endowed with a unit of time that can be allocated either to leisure, l_t, or to work, $v_t(= 1 - l_t)$. In this extended model, labor supply is determined by intertemporal utility maximization of a representative agent as in the literature on taxation vs. growth. There are four types of production activities in this economy: final good production, intermediate good production, physical capital accumulation and R&D. It is assumed that perfect competition prevails in all sectors except the intermediate good sectors where temporary monopoly power exists.

3.1. Final Good Production

There is a single final good which can be interchangeably used as a consumption or capital good or as an input to R&D. The final good is produced by labor and a continuum of intermediate goods according to the production function

$$Y_t = (G_{pt}/A_t)^{\beta} \int_0^1 A_{it} x_{it}^{\alpha} (v_t L)^{1-\alpha} di, \quad v_t + l_t = 1, \quad 0 < \alpha < 1, \quad 0 < \beta < 1 \quad (1)$$

where Y_t is the output of final good production at date t, G_{pt} the flow of services from government spending on the economy's infrastructure (we follow Turnovsky (2000) to assume that G_{pt} is a pure public good.), x_{it} the flow of intermediate good $i \in [0, 1]$ used in the final good production, A_{it} the productivity parameter attached with the latest version of intermediate goods i, $A_t \equiv \int_0^1 A_{it} di$ the average productivity parameter across all intermediate good sectors, α a parameter that measures the contribution of an intermediate good to the final good production and inversely measures the intermediate monopolist's market power, β a parameter that measures the contribution of public good (deflated by the average productivity parameter A_t) to the final good production, v_t the fraction of time allocated to work. In addition, we assume that government claims a fraction, g_p, of aggregate output, Y_t, for expenditure on infrastructure, in accordance with $G_{pt} = g_p Y_t$.

The final good producer chooses intermediate goods x_{it} and labor inputs $v_t L$ to maximize its profits

$$(G_{pt}/A_t)^{\beta} \int_0^1 A_{it} x_{it}^{\alpha} (v_t L)^{1-\alpha} di - \int_0^1 p_{it} x_{it} di - w_t v_t L, \tag{2}$$

where p_{it} is the price of intermediate good i and w_t is wage rate. Note that the final good is used as numeraire. The first-order conditions for this profit maximization problem are

$$p_{it} = \alpha (G_{pt}/A_t)^{\beta} A_{it} x_{it}^{\alpha-1} (v_t L)^{1-\alpha}, \quad \forall i \in [0, 1], \tag{3}$$

$$w_t = (1-\alpha)(v_t L)^{-\alpha} \int_0^1 A_{it} x_{it}^{\alpha} di. \tag{4}$$

These two conditions give the final good producer's demand for intermediate goods and labor. Note that as usual the quantities demanded of both intermediate goods and labor are negatively related to their respective prices p_{it} and w_t.

3.2. Intermediate Good Production

Each intermediate good i is produced using only capital K_{it} as its input. The technology for intermediate good production is given by $x_{it} = K_{it}/A_{it}$. In this specification, the capital input is deflated by the productivity parameter A_{it} to reflect the fact that more recent innovations are more capital intensive. Given the interest rate r_t and the final good producer's demand for the intermediate good (3), each intermediate good producer chooses its output x_{it} to maximize its monopoly profits

$$\pi_{it} = p_{it} x_{it} - r_t K_{it} = \alpha (G_{pt}/A_t)^{\beta} A_{it} x_{it}^{\alpha} (v_t L)^{1-\alpha} - r_t A_{it} x_{it}. \tag{5}$$

The first order condition for this maximization problem is

$$\alpha^2 (G_{pt}/A_t)^\beta A_{it} x_{it}^{\alpha-1} (v_t L)^{1-\alpha} - r_t A_{it} = 0, \quad \text{or} \quad \alpha^2 x_{it}^{\alpha-1} (v_t L)^{1-\alpha} - r_t = 0. \tag{6}$$

From (6), we can see that all intermediate good producers will produce the same amount of output, i.e., $x_{it} = x_t$, $\forall i \in [0,1]$, because each producer's marginal revenue and marginal cost are proportional to its productivity parameter A_{it}. Since the total demand for capital must be equal to the supply of capital, i.e., $\int_0^1 K_{it} di = \int_0^1 A_{it} x_{it} di = A_t x_t = K_t$, where K_t is the total capital stock, we have

$$x_t = K_t / A_t = k_t v_t L, \tag{7}$$

where $k_t \equiv K_t/(A_t v_t L)$ is the productivity-adjusted capital/labor ratio. Then equations (3), (5) and (6) give the optimal price of intermediate good i and the producer i's maximum profits

$$p_{it} = A_{it} \left(\frac{r_t}{\alpha} \right), \tag{8}$$

$$\pi_{it} = A_{it} \left(\frac{1-\alpha}{\alpha} \right) r_t k_t v_t L. \tag{9}$$

Note that both the optimal price and the maximum profits are proportional to the productivity parameter A_{it}.

3.3. R&D

Following Howitt and Aghion (1998), we assume that R&D takes the form of vertical innovations. Innovations are targeted at specific intermediate goods. Each innovation creates an improved version of the existing goods, replaces the existing one in final good production and produces final good more efficiently than before. R&D firms are motivated by the prospect of monopoly rents that can be captured when a successful innovation is patented. The successful innovator becomes the temporary monopolist until the arrival of the next innovation in that sector. R&D activities use final good as the only hired input. Suppose that innovations follow a Poisson process with the arrival rate $\phi_t = \lambda n_t$, where $\lambda(>0)$ is a parameter indicating the productivity of R&D and n_t is the productivity-adjusted quantity of final good devoted to R&D. R&D expenditure (in terms of final good) is $A_t^{max} n_t$, where $A_t^{max} \equiv \max\{A_{it} | i \in [0,1]\}$ is the productivity parameter of the leading-edge technology. The R&D expenditure increases with the leading-edge productivity parameter because innovation becomes increasingly complex as technology advances. Since the expected return on R&D investment is the same in each intermediate good sector, the amount of expenditure on R&D is also the same in each intermediate good sector. R&D firm chooses its input n_t to maximize its expected profits: $\lambda n_t V_t - (1 - s_n) A_t{}^{max} n_t$, where V_{it} is the expected value of a successful innovation and s_n the R&D subsidy/tax. The first-order conditions for this maximization problem are

$$\lambda V_t \leq (1 - s_n) A_t{}^{max}, \quad n_t \geq 0, \quad n_t[\lambda V_t - (1 - s_n) A_t{}^{max}] = 0, \tag{10}$$

where the value of a successful innovation V_t is given by the expected discounted present value of all the future profits the R&D firm can earn: $V_t = \int_t^\infty exp[-\int_t^s (r_z + \phi_z) dz] \pi_{ts} ds$, where s and z refer to time, r_z is the instantaneous rate of interest, ϕ_z is the rate of creative destruction (i.e., the instantaneous probability of being replaced by another innovation), and $\pi_{ts} \equiv \left(\frac{1-\alpha}{\alpha}\right) A_t^{max} r_s k_s v_s L$ is the profit flow to R&D firm. Setting the derivative of V_t equal to zero and using $\phi_t = \lambda n_t$ yields

$$V_t = \frac{\left(\frac{1-\alpha}{\alpha}\right) A_t^{max} r_t k_t v_t L}{r_t + \lambda n_t}. \tag{11}$$

Since we will only consider equilibria with $n_t > 0$, equations (10) and (11) imply

$$\frac{\left(\frac{1-\alpha}{\alpha}\right) \lambda r_t k_t v_t L}{r_t + \lambda n_t} = 1 - s_n, \tag{12}$$

which equalizes the expected marginal benefit (the left-hand side) and the marginal cost (the right-hand side) of R&D to determine the optimal investment in R&D.

3.4. Knowledge Spillover and Capital Accumulation

Following Caballero and Jaffe (1993), Aghion and Howitt (1998) and Zeng and Zhang (2002), we assume that growth in the leading-edge productivity ${A_t}^{max}$ results from knowledge spillover of vertical innovations. More specifically, the leading-edge productivity ${A_t}^{max}$ is assumed to grow at a rate proportionally to the aggregate rate of innovations λn_t; and the factor of this proportionality is assumed equal to $\sigma(> 0)$, which measures the marginal impact of the innovation to the stock of public knowledge. Since the aggregate flow of vertical innovations equals the number of intermediate sectors, which is normalized to one, times the number of vertical innovations in each sector λn_t, the growth rate of leading-edge productivity is

$$\dot{A}_t^{max}/{A_t}^{max} = \sigma\lambda n_t. \tag{13}$$

A dot on a variable represents the time change rate of that variable. As shown in Howitt and Aghion (1998), the ratio of leading-edge productivity A_t^{max} to the average productivity A_t converges monotonically to the constant $1 + \sigma$. Thus, it is assumed that $A_t^{max} = A_t(1 + \sigma)$ for all t, which also implies that $\dot{A}_t/A_t = \dot{A}_t^{max}/A_t^{max}$.

Final output is allocated among aggregate consumption (C_t), physical capital accumulation ($\dot{K}_t$), government expenditures on consumption and production (G_{ct} and G_{pt}, respectively) and R&D inputs (${A_t}^{max} n_t$). The market clearing condition for the final good gives the law of motion for capital stock

$$\dot{K}_t = Y_t - C_t - G_{ct} - G_{pt} - {A_t}^{max} n_t, \tag{14}$$

where we abstract from capital depreciation for simplicity.

3.5. Government

We assume that the government has access to distortionary taxes and subsidies (both at flat rates): a capital income tax τ_k, a labor income tax τ_w, a consumption tax τ_c, a capital investment subsidy s_k and a R&D subsidy s_n. We also assume that the lump-sum tax, T_t, is tied to aggregate output, Y_t, according to $T_t = g_T Y_t$.

Further assuming that the government's budget balances at each point in time, then we have the government's budget constraint

$$\tau_k r_t K_t + \tau_w w_t v_t L + \tau_c C_t + T_t = G_{ct} + G_{pt} + s_k \dot{K}_t + s_n {A_t}^{max} n_t. \tag{15}$$

In (15), the left-hand side is the government's tax revenue from capital income ($\tau_k r_t K_t$), labor income ($\tau_w w_t v_t L$), consumption ($\tau_c C_t$) and lump-sum tax (T_t). And the right-hand side is government's expenditures on consumption (G_{ct}) and infrastructure (G_{pt}) as well as the subsidies on capital investment ($s_k \dot{K}_t$) and innovation ($s_n {A_t}^{max} n_t$).

3.6. Preferences

The representative agent's welfare is given by the intertemporal isoelastic utility function

$$U = \int_0^\infty \frac{1}{\gamma} [\bar{c}_t {l_t}^\theta {G_{ct}}^\eta]^\gamma e^{-\rho t} dt,$$

$$\rho > 0,\ \eta > 0,\ \theta > 0,\ -\infty < \gamma \leq 1,\ \gamma(1+\eta) < 1,\ \gamma(1+\eta+\theta) < 1, \tag{16}$$

where $\bar{c}_t \equiv C_t/L$ is per capita private consumption; l_t is the fraction of time allocated to leisure; G_{ct} is the consumption services of a government-provided consumption good; ρ is the constant rate of time preference; γ is a parameter related to the intertemporal elasticity of substitution (χ say, by $\chi = 1/(1-\gamma)$), which requires $-\infty < \gamma \leq 1$; θ and η are parameters that respectively measure the importance of leisure and public consumption relative to private consumption. We assume that both leisure and public consumption provide the agent with positive marginal utility, which implies $\eta > 0$ and $\theta > 0$. The constraints $\gamma(1+\eta) < 1$ and $\gamma(1+\eta+\theta) < 1$

are required to ensure that the utility function is concave in $\bar{c}_t$, l_t and G_{ct}.[2]

We further assume that the government claims a fraction, g_c, of output for public consumption, i.e., $G_{ct} = g_c Y_t$. Given the public consumption goods provided by the government, the representative agent chooses his consumption $\bar{c}_t$ and leisure l_t to maximize his life-time discounted utility (16) subject to the following budget and time constraints

$$(1 - s_k)\dot{\bar{k}}_t = (1 - \tau_w)w_t v_t + (1 - \tau_k)r_t\bar{k}_t - (1 + \tau_c)\bar{c}_t - \overline{T}_t \ \text{(budget constraint)}, \tag{17}$$

$$v_t + l_t = 1 \ \text{(time constraint)}, \tag{18}$$

where $\bar{k}_t \equiv K_t/L$ is per capita capital asset; $\overline{T}_t \equiv T_t/L$ is per capita lump-sum tax.

Solving this optimization problem renders the optimal time path of per capita consumption

$$\frac{\dot{\bar{c}}_t}{\bar{c}_t} = \frac{1}{1 - \gamma(1 + \eta)} \left[\frac{r_t(1 - \tau_k)}{1 - s_k} - \rho\right], \tag{19}$$

and the relationship between leisure and consumption

$$\frac{\bar{c}_t}{l_t} = \frac{(1 - \tau_w)w_t}{(1 + \tau_c)\theta}. \tag{20}$$

In (19), the capital-income tax has a direct negative effect on consumption growth by reducing the after-tax rate of return to capital, while all taxes may affect consumption growth through the interest rate. In (20), a lower labor-income tax, or a lower consumption tax, tends to raise consumption relative to leisure by raising the after-tax wage, or by lowering the price of consumption.

[2]As noted in Turnovsky (2000), the utility function (16) satisfies the functional form identified by Ladrón-de-Guevara et al. (1997) for which the introduction of leisure will be consistent with a balanced growth equilibrium.

4. Equilibrium and Results

We consider only steady-state growth equilibria. The steady-state values of the interest rate r_t, R&D intensity n_t, capital intensity k_t and the proportion of time allocated to work v_t are all constant; and the aggregate output Y_t, capital stock K_t, private consumption C_t, public consumption G_{ct}, the average productivity A_t, the leading-edge productivity A_t^{max} and the wage rate w_t all grow at the same constant rate ψ. More formally, a steady-state balanced growth equilibrium is a collection of constant values (r, n, v, k) and a constant growth rate ψ for $\{Y_t, K_t, C_t, G_{ct}, A_t, A_t^{max}, w_t\}$ such that (i) each individual maximizes his lifetime utility by allocating his time between leisure and production and his income between consumption and saving; (ii) each (final good, intermediate good, and R&D) firm maximizes its profits; (iii) all the markets clear; and (iv) the government budget balances.

For notional simplicity, we define the quantity $\Gamma \equiv 1-\alpha+\alpha^2-g_c-g_p-\frac{\alpha(1-\alpha)(1+\sigma)s_n}{1-s_n}$. Carrying out the optimization for the consumer and aggregating over the L identical representative agents leads to the macroeconomic equilibrium which we now represent as follows

$$\frac{\theta v_t}{(1-\alpha)(1-v_t)}\left(\frac{C_t}{Y_t}\right) = \frac{1-\tau_w}{1+\tau_c} \tag{21}$$

$$\psi_t = \frac{1}{1-\gamma(1+\eta)}\left[\frac{\alpha^2(1-\tau_k)}{1-s_k}\left(\frac{Y_t}{K_t}\right)-\rho\right] \tag{22}$$

$$\psi_t = \left[\Gamma - \frac{C_t}{Y_t} + \frac{\alpha^2(1+\sigma)s_n}{\lambda(K_t/A_t)}\right]\left(\frac{Y_t}{K_t}\right) \tag{23}$$

$$\psi_t = \left[\frac{\sigma\lambda\alpha(1-\alpha)}{1-s_n}\left(\frac{K_t}{A_t}\right)-\sigma\alpha^2\right]\left(\frac{Y_t}{K_t}\right) \tag{24}$$

$$\frac{Y_t}{K_t} = \left[\left(\frac{K_t}{A_t}\right)^{\alpha+\beta-1} g_p^{\beta}(v_t L)^{1-\alpha}\right]^{\frac{1}{1-\beta}} \tag{25}$$

and which now determine the equilibrium values of: the fraction of time devoted to work, v_t, the consumption-output ratio, (C_t/Y_t), the output-capital ratio, (Y_t/K_t), the quantity of intermediate goods, (K_t/A_t), and the steady-state growth rate, ψ_t.

(21) describes the intratemporal optimality condition between consumption and leisure. It asserts that the marginal rate of substitution between labor and therefore output, and consumption equals the relative price of output in terms of consumption. (22) is the Euler equation which equates the social marginal return to capital to the rate of return on consumption. (23) is the aggregate resource constraint per unit of capital. (24) simply states the fact that at the equilibrium output and leading-edge productivity grow at the same rate. Finally, (25) restates the production function.

To avoid obscuring the main focus of the paper, we consider only unique equilibrium. Before proceeding to describe the results, we identify the conditions that guarantee a unique steady-state growth equilibrium.

Proposition 1. *A unique steady-state growth equilibrium exists provided that the following conditions are met.*

$$\frac{(1-\beta)[1-\gamma(1+\eta)]}{\theta\alpha^2} > \frac{(1+\tau_c)(1-\tau_k)}{(1-\tau_w)(1-s_k)} \tag{26}$$

$$\frac{1-\tau_w}{\theta(1+\tau_c)}\left\{\frac{\sigma(1-\beta)[1-\gamma(1+\eta)](1-s_k)}{1-\tau_k} + (1-\alpha-\beta)\right\} - \sigma\alpha^2$$
$$> \alpha(1-\alpha)(1+\sigma)\left(\frac{s_n}{1-s_n}\right) \tag{27}$$

$$\frac{(1-\alpha)(1-\tau_w)}{\theta(1+\tau_c)}\left\{g_p^{\frac{\beta}{1-\alpha}}\left[\frac{\rho(1-s_k)}{\alpha^2(1-\tau_k)}\right]^{\frac{\beta-1}{1-\alpha}}\left[\frac{\lambda(1-\alpha)}{\alpha(1-s_n)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}} - 1\right\}$$
$$> 1-\alpha+\alpha^2 - g_c - g_p \tag{28}$$

If we interpret the term $\frac{1-\tau_k}{1-s_k}$ as the net subsidy on capital income and the term $\frac{1-\tau_w}{1+\tau_c}$ as the net tax on labor income, then (26) says that the ratio of net subsidy on capital income to net tax on labor income should be upper-bounded. In other words, capital cannot be overly subsidized.

Using (26), we can deduce that the left-hand side of (27) is strictly positive.

$$\frac{1-\tau_w}{\theta(1+\tau_c)}\left\{\frac{\sigma(1-\beta)[1-\gamma(1+\eta)](1-s_k)}{1-\tau_k}+(1-\alpha-\beta)\right\}-\sigma\alpha^2$$

$$>\frac{1-\alpha-\beta}{\alpha(1-\alpha)(1+\sigma)}$$

$$>0$$

Therefore, (27) imposes a restriction on the magnitude of s_n. If $s_n < 0$ (i.e., R&D taxes), (27) will be readily satisfied. If $s_n > 0$, the right-hand side of (27), which has to be upper-bounded, is simply the ratio of R&D subsidy per unit to R&D cost per unit. This requires that R&D not be excessively subsidized.

(28) is to rule out the possibility of no growth. Recall that (23) is the aggregate resource constraint per unit of capital. Hence, (28) can be rewritten as

$$1-\alpha+\alpha^2-g_c-g_p-\left(\frac{C_t}{Y_t}\right)_{\psi=0}<0$$

where

$$\left(\frac{C_t}{Y_t}\right)_{\psi=0}=\frac{(1-\alpha)(1-\tau_w)}{\theta(1+\tau_c)}\left\{g_p^{\frac{\beta}{1-\alpha}}\left[\frac{\rho(1-s_k)}{\alpha^2(1-\tau_k)}\right]^{\frac{\beta-1}{1-\alpha}}\left[\frac{\lambda(1-\alpha)}{\alpha(1-s_n)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}}-1\right\}$$

is the consumption-output ratio when the growth rate is zero. Then (28) says that the aggregate resource constraint will be violated if there is no growth.

Under Proposition 1, the equilibrium values of (Y_t/K_t), (K_t/A_t), (C_t/Y_t), v_t and ψ_t are implicitly determined by (time subscripts are omitted for neatness)

$$\frac{Y}{K}=\frac{(1-s_k)\{\rho+[1-\gamma(1+\eta)]\psi\}}{\alpha^2(1-\tau_k)} \tag{29}$$

$$\frac{K}{A}=\frac{(1-s_n)[\psi+\sigma\alpha^2 f(\psi)]}{\sigma\lambda\alpha(1-\alpha)f(\psi)} \tag{30}$$

$$\frac{C}{Y}=\frac{(1-\alpha)(1-\tau_w)}{\theta(1+\tau_c)}\left\{Lg_p^{\frac{\beta}{1-\alpha}}f(\psi)^{\frac{\beta-1}{1-\alpha}}\left\{\frac{(1-s_n)[\psi+\sigma\alpha^2 f(\psi)]}{\sigma\lambda\alpha(1-\alpha)f(\psi)}\right\}^{\frac{\alpha+\beta-1}{1-\alpha}}-1\right\} \tag{31}$$

$$v = L^{-1} g_p^{\frac{\beta}{\alpha-1}} f(\psi)^{\frac{1-\beta}{1-\alpha}} \left\{ \frac{(1-s_n)[\psi + \sigma\alpha^2 f(\psi)]}{\sigma\lambda\alpha(1-\alpha)f(\psi)} \right\}^{\frac{\alpha+\beta-1}{\alpha-1}} \tag{32}$$

$$\begin{aligned} \psi \;&=\; f(\psi)\left\{\Lambda_1 + \sigma\alpha^3(1-\alpha)(1+\sigma)\left(\frac{s_n}{1-s_n}\right)\frac{f(\psi)}{\psi+\sigma\alpha^2 f(\psi)}\right\} \\ &\quad -\frac{(1-\alpha)(1-\tau_w)f(\psi)}{\theta(1+\tau_c)}\left\{L g_p^{\frac{\beta}{1-\alpha}} f(\psi)^{\frac{\beta-1}{1-\alpha}}\left\{\frac{(1-s_n)[\psi+\sigma\alpha^2 f(\psi)]}{\sigma\lambda\alpha(1-\alpha)f(\psi)}\right\}^{\frac{\alpha+\beta-1}{1-\alpha}} - 1\right\}, \end{aligned} \tag{33}$$

where $f(\psi) \equiv \frac{(1-s_k)\{\rho+[1-\gamma(1+\eta)]\psi\}}{\alpha^2(1-\tau_k)}$.

In the next chapter, we will carry on welfare analysis for the decentralized economy. To provide a benchmark, we also give the social planner's solution next.

Social Planner's Problem

At each point in time, social planner sets production plan for every producer. Specifically, social planner chooses x_{it} to maximize the quantity of final good subject to the resource constraint, $\int_0^1 A_{it}x_{it}di = K_t$. The first order condition for this optimization problem yields $x_{it} = v_t L(g_p/A_t)^{\frac{\beta}{1-\alpha}} \theta^{\frac{1}{\alpha-1}}$. Note that this quantity is independent of i. Hence, each intermediate good producer in the centrally planned economy supplies the same quantity of intermediate good $x_{it} = x_t = K_t/A_t$.

The social planner chooses (C_t, G_{ct}, G_{pt}, K_t, n_t, v_t) to maximize the representative agent's utility described by Eq.(16) subject to the following resource and technology constraints

$$\dot{K}_t = (1-g_c-g_p)Y_t - C_t - (1+\sigma)A_t n_t \;\; \text{(resource constraint)} \tag{34}$$

$$\dot{A}_t/A_t = \sigma\lambda n_t \;\; \text{(technology constraint)} \tag{35}$$

The social optimum can be summarized by the following five equations.

$$\widetilde{\left(\frac{Y}{K}\right)} = \frac{\rho + [1-\gamma(1+\eta)]\tilde{\psi}}{\alpha} \tag{36}$$

$$\widetilde{\left(\frac{K}{A}\right)} = \frac{\alpha(1+\sigma)}{\sigma\lambda(1-\alpha-\beta)} \tag{37}$$

$$\widetilde{\left(\frac{C}{Y}\right)} = \frac{1-\alpha}{\theta}\left\{L\beta^{\frac{\beta}{1-\alpha}}h(\tilde{\psi})^{\frac{\beta-1}{1-\alpha}}\left[\frac{\alpha(1+\sigma)}{\sigma\lambda(1-\alpha-\beta)}\right]^{\frac{\alpha+\beta-1}{1-\alpha}} - 1\right\} \tag{38}$$

$$\tilde{v} = L^{-1}\beta^{\frac{\beta}{\alpha-1}}h(\tilde{\psi})^{\frac{1-\beta}{1-\alpha}}\left[\frac{\alpha(1+\sigma)}{\sigma\lambda(1-\alpha-\beta)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}} \tag{39}$$

$$\tilde{\psi} = \alpha h(\tilde{\psi}) - \frac{\alpha(1-\alpha)(1+\eta)}{\theta(1-\beta)}h(\tilde{\psi})\left\{L\beta^{\frac{\beta}{1-\alpha}}h(\tilde{\psi})^{\frac{\beta-1}{1-\alpha}}\left[\frac{\alpha(1+\sigma)}{\sigma\lambda(1-\alpha-\beta)}\right]^{\frac{\alpha+\beta-1}{1-\alpha}} - 1\right\} \tag{40}$$

where $h(\tilde{\psi}) \equiv \frac{\rho+[1-\gamma(1+\eta)]\tilde{\psi}}{\alpha}$.

In the centrally planned economy, one can show that a unique balanced growth equilibrium exists under the condition

$$\gamma < \frac{\rho(1-\beta)\left[\frac{\alpha(1+\sigma)}{\sigma\lambda(1-\alpha-\beta)}\right]^{\frac{1-\alpha-\beta}{1-\beta}}}{\alpha(1+\eta)(1-g_c-g_p)L^{\frac{1-\alpha}{1-\beta}}g_p^{\frac{\beta}{1-\beta}}} \tag{41}$$

which would plausibly be met given the empirical evidence suggesting that $\gamma < 0$. Compared with decentralized equilibrium, the parallels between equations (29)-(32) and equations (36)-(39) are clear. The main difference is that in the decentralized economy the agent takes the policy of government as given and responds to tax incentives. It should be noted that the shape of the agent's preference function is identical to that in Turnovsky (2000). As a consequence, the effects of social planner's policy on the equilibrium are the same as obtained by Turnovsky (2000).

5. Optimal Fiscal Policy

In this chapter, we address the question of optimal fiscal policy and consider the extent to which the policy maker in the decentralized economy is able to set expenditure and tax rates so that the equilibrium in that economy, described by equations (29)-(33), replicates the first-best outcome obtained by the social planner, described by equations (36)-(40).

First-best fiscal policy

The government chooses (g_c, g_p, τ_c, τ_w, τ_k, s_n) to maximize the representative agent's welfare (16). Here both $g_T \geq 0$ and $s_k \geq 0$ are treated as exogenously given. This treatment has no essential effect on our analysis of optimal fiscal policy. The first-best fiscal policy is given by

Proposition 2. *Let* $F(g_c^*) \equiv \rho\eta(1-\beta)\{\alpha(1+\eta)\{\gamma\eta(1-\beta) + [1-\gamma(1+\eta)]g_c^*\}\}^{-1}$ *and* $\delta_1 \equiv -\gamma\eta(1-\beta)/[1-\gamma(1+\eta)]$. *For* $(1,1) > (g_T^*, s_k^*) \geq (0,0)$, *if*

$$\frac{\rho}{\alpha\gamma(1+\eta)} < 0 \tag{42}$$

and

$$\beta^{\frac{\beta}{1-\alpha}} \left[\frac{\sigma\lambda(1-\alpha-\beta)}{\alpha(1+\sigma)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}} \left[\frac{\rho}{\alpha\gamma(1+\eta)}\right]^{\frac{\beta-1}{1-\alpha}} > 1 \tag{43}$$

then there exists a unique $g_c^* \in (0, \delta_1)$ *that supports the first best fiscal policy which is:* $g_p^* = \beta$, $\tau_k^* = 1 - (1 - s_k^*)/\alpha$ *and*

$$g_c^* = \frac{\eta(1-\alpha)}{\theta} \left\{\beta^{\frac{\beta}{1-\alpha}} \left[\frac{\sigma\lambda(1-\alpha-\beta)}{\alpha(1+\sigma)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}} F(g_c^*)^{\frac{\beta-1}{1-\alpha}} - 1\right\} \tag{44}$$

$$s_n^* = 1 - \frac{\alpha(1-\alpha)(1+\sigma)}{(1-\alpha-\beta)\{1+\sigma\alpha-(1+\eta)g_c^*/[\eta(1-\beta)]\}} \tag{45}$$

$$\tau_c^* = -\tau_w^* = \frac{(1-s_k^*)\left[\alpha+\beta-\alpha^2+g_c^*+\alpha(1+\sigma)s_n^*\left(\frac{1-\alpha}{1-s_n^*}-\frac{1-\alpha-\beta}{1+\sigma}\right)\right]-g_T^*}{(g_c^*/\eta)-(1-\alpha)} - s_k^* \tag{46}$$

The optimal government expenditures are derived from maximizing the current-value Hamiltonian in the Appendix A.2. with respect to g_c and g_p. The optimal taxation arises from equalizing the decentralized solutions and social planner's solutions by choosing the tax and subsidy rates as well as the shares of output devoted to public consumption and infrastructure. Note that s_n can be either positive or negative. In cases that it is negative, s_n can be explained as R&D taxes. Note also that the first-best scheme at $\tau_k = 0$ is equivalent to schemes at $\tau_k > 0$ so long as the rules specified above are met.

Our findings for the first-best tax scheme are at odds with Turnovsky (2000) in two aspects. First, R&D subsidies/taxes may be necessary for sustaining first-best outcome. The government's intervention on R&D is justified by the two effects associated with R&D, namely, 'appropriability effect' and 'business-stealing effect'. 'Appropriability effect', which reflects the private monopolists' inability to appropriate the whole output flow (he or she can appropriate only a fraction $(1 - \alpha)$ of that output), tends to generate too little research under laissez-faire and too low a growth rate. 'Business-stealing effect', which arises from the failure of private research firm to internalize the loss to the previous monopolist caused by an innovation, will tend to generate too much research under laissez-faire and thus too high a growth rate. In contrast, the social planner takes into account that an innovation destroys the social return from the previous innovation.

Second, the first-best tax structure in Turnovsky (2000) is characterized by a zero tax on capital income. In our model, however, mere a zero tax on capital income is not enough. To replicate first-best outcome, it requires capital investment be subsidized. This is due to the presence of monopoly power in intermediate-good sectors. With monopoly power in intermediate-good sectors, investment allocation is always sub-optimal. Hence investment subsidies are called for to the extent that an ideal level of investment is met. In order for investment subsidies to correct tax distortions in addition to monopoly distortions, they must be greater than the tax on capital income. In particular, the subsidies on capital investment depend positively on the monopoly power in intermediate-good sectors (i.e., s_k becomes larger when α is smaller).

In agreement with Turnovsky (2000), the optimal tax structure also requires that consumption and leisure be taxed uniformly. A special case here is to set $s_k = 1 - \alpha$ on capital investment and a zero tax on capital income, and to tax consumption and leisure equally.

The government's intervention on R&D, represented by s_n, is a key difference between our model and previous work. It is therefore of interest to identify the parameters that govern the sign of s_n.

Proposition 3. *Let* $\delta_2 \equiv \eta(1-\beta)(1+\eta)^{-1}[1+\sigma\alpha - \alpha(1-\alpha)(1+\sigma)(1-\alpha-\beta)^{-1}]$. *If* $\delta_1 < \delta_2$, $s_n^* > 0$. *If* $\delta_1 > \delta_2$, s_n^* *is signed by*

$$sgn(s_n^*) = sgn\left\{1 - \frac{\eta(1-\alpha)}{\theta}\left\{\beta^{\frac{\beta}{1-\alpha}}\left[\frac{\sigma\lambda(1-\alpha-\beta)}{\alpha(1+\sigma)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}} F(\delta_2)^{\frac{\beta-1}{1-\alpha}} - 1\right\}\right\} \quad (47)$$

If $\delta_1 < \delta_2$, there have to be subsidies on R&D. Since δ_2 is decreasing in σ and α, the inequality $\delta_1 < \delta_2$ would be satisfied if σ and/or α are/is very small. Therefore, R&D subsidies are necessary if the spillover effect is very small or monopoly power is very strong. The economic intuition is as follows. (i) Too small spillover effect leads to a sub-optimal growth rate and too low welfare. By subsidizing R&D, the government reduce the marginal cost of R&D (the right-hand side of (12)). This gives R&D firms the incentive to increase R&D intensity n_t until the marginal cost and marginal gain (the left-hand side of (12)) are equalized. (ii) As α is very small (indicating very strong monopoly power), so are the monopoly profits, and so is the expected marginal gain of R&D. Hence, R&D subsidies are called for to reduce the marginal cost of R&D to the extent that marginal cost equals expected marginal gain.

If $\delta_1 > \delta_2$, the sign of s_n depends crucially upon (i) the magnitude of knowledge spillover σ and (ii) the magnitude of the productivity parameter λ. R&D taxes (i.e. $s_n < 0$) become relevant if σ and/or λ are/is too large. σ affects the sign of s_n in the same way as described for the case $\delta_1 < \delta_2$. The parameter of R&D productivity λ has two-fold effects on social welfare. Notice that the R&D productivity parameter λ enters both the numerator and denominator of the left-hand side of (12). On one hand, a rise in λ increases the rate of creative destruction λn_t. A high rate of creative destruction discourages R&D because current technology will be more easily superseded when the rate of creative destruction is high. On the other hand, it raises the profit flow π_{ts} to R&D firm, thereby increasing the incentive to make innovation. As a result, a rise in R&D productivity can both decrease and increase the marginal gain of R&D. Here it is clear that the latter effect dominates. Accordingly, too large λ calls for R&D taxes to avoid too much R&D. In addition, the effect of monopoly power $1/\alpha$ on the sign of s_n is quite ambiguous.

For the parameters of our benchmark economy, i.e. $\alpha = 0.3, \beta = 0.08, \eta = 0.3, \gamma = -1, \sigma = 0.1$, the inequality $\delta_1 < \delta_2$ will be met. Hence, R&D subsidies are always relevant for our benchmark economy. Note that except the value of σ which is chosen arbitrarily, the other parameters values are representative of the U.S. economy. This is consistent with the observation in the real world that the governments usually choose to subsidize R&D.

The existence of first-best scheme is contingent upon conditions (42) and (43). Given empirical evidence suggesting that $\gamma < 0$, (42) would plausibly be met. However, (43) is hard to verify since it includes the knowledge spillover σ as well as the R&D productivity parameter λ for which we have no empirical evidence. Furthermore, $\left[\frac{\rho}{\alpha\gamma(1+\eta)}\right]^{\frac{\beta-1}{1-\alpha}}$ is not defined everywhere for $(\alpha, \beta) \in (0,1) \times (0,1)$ if $\gamma < 0$. In this kind of situation, the focus should then be placed on second-best policy.

Second-best fiscal policy

The second-best fiscal policy is derived from maximizing economic welfare subject to the government budget constraint. Economic welfare is the optimized utility of the representative agent, which evaluates to

$$W = \frac{[(C/Y)l^{\theta}g_c^{\eta}(Y/K)^{1+\eta}]^{\gamma}}{\gamma[\rho - \gamma(1+\eta)\psi]} \tag{48}$$

after normalizing the population and initial capital stock (L and K_0, respectively) to one.

Given that explicit solutions cannot be derived in this case, numerical analysis are helpful in highlighting the welfare effects of fiscal policy. We begin by characterizing a benchmark economy, by calibrating the model using the following parameters: $\alpha = 0.3, \beta = 0.08, \gamma = -1, \rho = 0.05, \theta = 0.3, \eta = 0.3, \lambda = 0.5, \sigma = 0.1, g_c = 0.14, g_p = 0.08, g_T = 0$. Except λ and σ which we choose arbitrarily, the other parameters' values are representative of the U.S. economy. In the United States, the historical average of the total fraction of net national production devoted to government expenditure on goods and services equals 0.22. That is why we choose $g_c + g_p = 0.22$. Following Turnovsky (2000), the breakdown point is chosen at $g_c = 0.14$ and $g_p = 0.08$.

Table 1 reports the simulation results for the general case. Across the columns, we give the values of the different tax rates and subsidy rates. We begin with the case without investment subsidies and R&D subsidies, in which we compare the welfare effects of consumption taxation, labor-income taxation and capital-income taxation. First, if the government choose only one kind of taxation to collect revenue, then consumption taxation is better than income taxation from welfare perspective. This finding is compatible with the existing literature. Second, if the government impose the same tax rate on labor income and capital income, then transforming income taxation toward consumption taxation can be welfare reducing. This finding is in line with Davies et al. (2002). Davies et al. (2002) show that a tax mix similar to US practice is better than consumption alone once investment subsidies are allowed. Through our simulation we can see that if labor income taxation and capital income taxation are chosen equally, a transition from income taxation to consumption taxation will be welfare reducing even without investment subsidies.

Next, we set $\tau_w = \tau_k = 0.25$, which is close to the income tax rates in the United States. Under this setting, we observe that an increase in the subsidy rates on capital investment and R&D can improve welfare marginally. Hence, even if it is impossible to implement first-best policy, we are still able to use investment subsidies and R&D subsidies to improve welfare.

Table 2 reports simulation results as the values of α and σ vary. To compare with the results in Table 1, we set $\tau_w = \tau_k = 0.25$. We can see that investment subsidies and R&D subsidies increase as α falls. A small α corresponds to strong monopoly power in intermediate-good sector. Strong monopoly power requires larger capital subsidy to reduce the distortions in capital investment. Since a decline in α depresses the accumulated profit of R&D, the government need to raise R&D subsidies to stimulate R&D expenditure. On the other hand, as σ rises, the government need to reduce R&D subsidies. The economic intuition is as follows. When the spillover effect is too large, the government need to decrease R&D subsidies to reduce the incentive for R&D investment. Therefore, the simulation results confirm our findings for the welfare effects of investment subsidies and R&D subsidies.

6. Conclusions

In this thesis, we use Schumpeterian growth model with endogenous labor supply to investigate optimal fiscal policy. We show that investment subsidies and R&D subsidies play important roles in the optimal fiscal policy for technology-leading economies.

Our findings for the first-best fiscal policy are summarized as follows. First of all, the first-best tax structure requires consumption and leisure be taxed uniformly. Leisure can be deemed as a kind of consumption good. At the optimum, any two consumption goods have to be taxed equally.

Second, investment subsidies, which positively depend on the degree of monopoly power, are required in the first-best policy. Furthermore, investment subsidies must be greater than capital-income tax. The economic intuition is that in order for the social welfare to be first best, the distortions in capital investment caused by monopoly and capital-income tax require investment subsidies to correct.

Finally, the government's R&D policy in terms of R&D subsidies/taxes may be necessary for replicating the first-best outcome. More specifically, when the spillover effect is very small or monopoly power is very strong, R&D subsidies can help increase welfare by reducing the marginal cost of R&D and maintaining the optimal level of R&D input. When the size of innovation is very large or the R&D productivity is very high, R&D taxes are required to prevent too much R&D investment. Nevertheless, under plausible parameterization, only R&D subsidies are relevant for first-best policy. This is consistent with empirical evidence.

The first result is well-known in the literature. The second result is consistent with Guo and Lansing (1999). If tax on capital income is allowed to be negative in our model, we can also have negative, positive or zero optimal tax on capital income when the magnitude of investment subsidy varies. A negative tax is in fact a subsidy. In that sense, our second finding parallels Guo and Lansing (1999). This result is, however, different from Turnovsky (2000) in which product markets are perfectly competitive. The third finding is new to our knowledge. Although Howitt and Aghion (1998) examined the growth effects of investment subsidies and R&D subsidies, the welfare effects of R&D subsidies remain unaddressed. In that sense, our results complement those in the existing literature.

Given that the existence of first-best policy is hard to verify, we then focus on numerical analysis of the welfare effects of investment subsidies and R&D subsidies. Simulation results reveal that both investment subsidies and R&D subsidies can help increase welfare even when the first-best policy is unavailable. Thus, the implication of this thesis is that investment subsidies and R&D subsidies can improve welfare in technology-leading economies

References

Aghion, P., Howitt, P., 1992. A model of growth through creative destruction. Econometrica 60, 323-351

Aghion, P., Howitt, P., 1998. Endogenous growth theory. Cambridge, MA: MIT Press.

Barro, R.J., 1990. Government spending in a simple model of endogenous growth. Journal of Political Economy 98, S103-S125

Barro, R.J., Sala-i-Martin, X., 1995. Economic growth. New York: McGraw-Hill.

Bruce, N., Turnovsky, S.J., 1999. Budget balance, welfare, and the growth rate:'dynamic scoring' of the long-run government budget. Journal of Money, Credit and Banking 31, 162-186.

Caballero, R.J., Jaffe., A.B., 1993. How high are the giants' shoulders: an empirical assessment of knowledge spillovers and creative destruction in a model of economic growth. NBER Macroeconomics Annual, 1993. Cambridge, MA: MIT Press.

Chamley, C., 1986. Optimal taxation of capital income in general equilibrium with infinite lives. Econometrica 54. 607-622.

Davies, J., Zeng, J., Zhang, J., 2002. Can home production challenge consumption taxation? National University of Singapore, Department of Economics, Working Paper.

Deaton, A., 1981. Optimal taxes and the structure of preferences. Econometrica 49, 1245-1260.

Eaton, J., 1981. Fiscal policy, inflation, and the accumulation of risky capital. Review of Economic Studies 48, 435-445.

Grossman, G.M., Helpman, E., 1991. Innovation and growth in the global economy. MIT Press, Cambridge.

Guo, J.T., Lansing, K.J., 1999. Optimal taxation of capital income with imperfectly competitive product markets. Journal of Economic Dynamics and Control 23, 967-995.

Hall, R.E., 1988. Intertemporal substitution in consumption. Journal of Political Economy 96, 339-357.

Howitt, P., Aghion, P., 1998. Capital accumulation and innovation as complementary factors in long-run growth. Journal of Economic Growth 3, 111-130

Ireland, P., 1994. Supply-side economics and endogenous growth. Journal of Monetary Economics 33, 559-571.

Jones, L.E., Manuelli, R.E., Rossi, P.E., 1993. Optimal taxation in models of endogenous growth. Journal of Political Economy 101, 485-517.

Jones, L.E., Manuelli, R., Rossi, P.E., 1997. On the optimal taxation of capital income. Journal of Economic Theory 73, 93-117.

Judd, K.L., 1999. Optimal taxation and spending in general competitive growth models. Journal of Public Economics 71, 1-26.

King, R.E., Rebelo, S., 1990. Public policy and economic growth: developing neoclassical implications. Journal of Political Economy 98, S126-S151.

Krusell, P., Quadrini, V., Ríos-Rull, J.-V., 1996. Are consumption taxes really better than income taxes? Journal of Monetary Economics 37, 475-503.

Ladrón-de-Guevara, A., Ortigueira, S., Santos, M.S., 1997. Equilibrium dynamics in two-sector models of endogenous growth. Journal of Economic Dynamics and Control 21, 115-143.

Lucas, R.E., 1988. On the mechanics of economic development. Journal of Monetary Economics 22, 3-42.

Lucas, R.E., Stokey, N.L., 1983. Optimal fiscal and monetary policy in an economy without capital. Journal of Political Economy 101, 55-93.

Milesi-Ferretti, G.M., Roubini, N., 1998b. Growth effects of income and consumption taxes. Journal of Money, Credit and Banking 30 (4), 721-744.

Peretto, P.F., 1997. The dynamic effects of taxes and subsidies on market structure and economic growth. Duke University, Department of Economics, Working Paper No. 97-12

Ramsey, F.P., 1927. A contribution to the theory of taxation. Economic Journal 37, 47-61

Romer, P.M., 1990. Endogenous technological change. Journal of Political Economy 98, S71-S102.

Rebelo, S., 1991. Long-run policy analysis and long-run growth. Journal of Political Economy 99, 500-521.

Stokey, N.L., Rebelo, S., 1995. Growth effects of flat-rate taxes. Journal of Political Economy 103, 519-550.

Summers, L., 1981. Capital taxation and accumulation in a life-cycle growth model. American Economic Review 71, 533-544.

Turnovsky, S.J., 1996. Optimal tax, debt, and expenditure policies in a growing economy. Journal of Public Economics 60, 21-44.

Turnovsky, S.J., 2000. Fiscal policy, elastic labor supply, and endogenous growth. Journal of Monetary Economics 45, 185-210.

Zeng, J., Zhang, J., 2002. Long-run growth effects of taxation in a non-scale growth model with innovation. Economics Letters 75, 391-403.

Appendices

A.1. Proof of the convergence of A_t^{max} to $A_t(1+\sigma)$.

Defining $\Theta \equiv A_t^{max}/A_t$. Taking the logarithm of both sides and then differentiating with respect to time t, we have,

$$\frac{1}{\Theta} \times \frac{d\Theta}{dt} = \frac{\dot{A}_t^{max}}{A_t^{max}} - \frac{\dot{A}_t}{A_t} = \frac{\dot{A}_t^{max}}{A_t^{max}} - \frac{\phi_t(A_t^{max} - A_t)}{A_t} = \phi_t\sigma - \phi_t(\Theta - 1) = \phi_t(1+\sigma-\Theta)$$

In the long run, the growth rate of Θ should be equal to zero to achieve a stable equilibrium, therefore we have $\phi_t(1+\sigma-\Theta) = 0$. Since ϕ_t is always positive, we must have $\Theta = 1+\sigma$ which implies $A_t^{max} = A_t(1+\sigma)$ and $\dot{A}_t^{max}/A_t^{max} = \dot{A}_t/A_t = g$.

A.2. The optimality conditions for decentralized economy

The current-value Hamiltonian to the optimization problem of representative agent is

$$H \equiv \frac{1}{\gamma}(\bar{c}_t l_t^{\theta} G_{ct}^{\eta})^{\gamma} + \frac{\Lambda_t}{1-s_k}[(1-\tau_w)w_t(1-l_t) + (1-\tau_k)r_t\bar{k}_t - (1+\tau_c)\bar{c}_t - \overline{T}_t] \quad (49)$$

The optimality conditions are

$$\frac{\partial H}{\partial \bar{c}_t} = \bar{c}_t^{\gamma-1}(l_t^{\theta}G_{ct}^{\eta})^{\gamma} - \frac{\Lambda_t(1+\tau_c)}{1-s_k} = 0, \quad (50)$$

$$\frac{\partial H}{\partial l_t} = \theta\gamma(\bar{c}_t G_{ct}^{\eta})^{\gamma} l_t^{\theta\gamma-1} - \frac{\Lambda_t(1-\tau_w)w_t}{1-s_k} = 0, \quad (51)$$

$$\frac{\partial H}{\partial \bar{k}_t} = \frac{\Lambda_t(1-\tau_k)r_t}{1-s_k} = \rho\Lambda_t - \dot{\Lambda}_t, \quad (52)$$

$$\lim_{t\to\infty} e^{-\rho t}\Lambda_t\bar{k}_t = 0, \quad (53)$$

(17) and (18), where (53) is a transversality condition. From the above first-order conditions, we obtain the optimal path of (per capita) private consumption (19) and the relationship between leisure and consumption (20).

A.3. Derivation of Proposition 1

Let $\Omega(\psi)$ represent the right hand side of Eq.(33). Differentiating $\Omega(\psi)$ with respect to ψ, we have

$$\begin{aligned}\frac{\partial\Omega}{\partial\psi} &= \frac{(1-\tau_w)(1-s_k)}{\theta\alpha^2(1+\tau_c)(1-\tau_k)} g_p^{\frac{\beta}{1-\alpha}} f(\psi)^{\frac{\beta-1}{1-\alpha}} \left\{\frac{\sigma\lambda\alpha(1-\alpha)f(\psi)}{(1-s_n)[\psi+\sigma\alpha^2 f(\psi)]}\right\}^{\frac{1-\alpha-\beta}{1-\alpha}} \\ & \left\{(1-\beta)[1-\gamma(1+\eta)] + \frac{\rho(1-\alpha-\beta)}{\psi+\sigma\alpha^2 f(\psi)}\right\} \\ & -\sigma\alpha(1-\alpha)(1+\sigma)\left(\frac{s_n}{1-s_n}\right)\frac{\rho(1-s_k)f(\psi)}{(1-\tau_k)[\psi+\sigma\alpha^2 f(\psi)]} \\ & +\frac{\partial f}{\partial\psi}\left\{\Lambda_1 + \sigma\alpha^3(1-\alpha)(1+\sigma)\left(\frac{s_n}{1-s_n}\right)\frac{f(\psi)}{\psi+\sigma\alpha^2 f(\psi)}\right\}\end{aligned}$$

$\partial\Omega/\partial\psi > 1$ if the sum of the first two terms is greater than 1. Using the fact $(C_t/Y_t) > 0$, we have

$$g_p^{\frac{\beta}{1-\alpha}} f(\psi)^{\frac{\beta-1}{1-\alpha}} \left\{\frac{\sigma\lambda\alpha(1-\alpha)f(\psi)}{(1-s_n)[\psi+\sigma\alpha^2 f(\psi)]}\right\}^{\frac{1-\alpha-\beta}{1-\alpha}} > 1$$

Therefore

$$\begin{aligned}& \frac{(1-\tau_w)(1-s_k)}{\theta\alpha^2(1+\tau_c)(1-\tau_k)} g_p^{\frac{\beta}{1-\alpha}} f(\psi)^{\frac{\beta-1}{1-\alpha}} \left\{\frac{\sigma\lambda\alpha(1-\alpha)f(\psi)}{(1-s_n)[\psi+\sigma\alpha^2 f(\psi)]}\right\}^{\frac{1-\alpha-\beta}{1-\alpha}} \\ & \left\{(1-\beta)[1-\gamma(1+\eta)] + \frac{\rho(1-\alpha-\beta)}{\psi+\sigma\alpha^2 f(\psi)}\right\} \\ & -\sigma\alpha(1-\alpha)(1+\sigma)\left(\frac{s_n}{1-s_n}\right)\frac{\rho(1-s_k)f(\psi)}{(1-\tau_k)[\psi+\sigma\alpha^2 f(\psi)]} \\ & > \frac{(1-\tau_w)(1-s_k)}{\theta\alpha^2(1+\tau_c)(1-\tau_k)} \left\{(1-\beta)[1-\gamma(1+\eta)] + \frac{\rho(1-\alpha-\beta)}{\psi+\sigma\alpha^2 f(\psi)}\right\} \\ & -\sigma\alpha(1-\alpha)(1+\sigma)\left(\frac{s_n}{1-s_n}\right)\frac{\rho(1-s_k)f(\psi)}{(1-\tau_k)[\psi+\sigma\alpha^2 f(\psi)]}\end{aligned}$$

Next we want to derive the conditions for the inequality below to hold.

$$\frac{(1-\tau_w)(1-s_k)}{\theta\alpha^2(1+\tau_c)(1-\tau_k)}\left\{(1-\beta)[1-\gamma(1+\eta)]+\frac{\rho(1-\alpha-\beta)}{\psi+\sigma\alpha^2 f(\psi)}\right\}$$

$$-\sigma\alpha(1-\alpha)(1+\sigma)\left(\frac{s_n}{1-s_n}\right)\frac{\rho(1-s_k)f(\psi)}{(1-\tau_k)[\psi+\sigma\alpha^2 f(\psi)]}$$

$$>1$$

which is equivalent to

$$\frac{1-\tau_w}{\theta(1+\tau_c)}\left\{(1-\beta)[1-\gamma(1+\eta)]-\frac{\theta\alpha^2(1+\tau_c)(1-\tau_k)}{(1-\tau_w)(1-s_k)}\right\}\frac{[\psi+\sigma\alpha^2 f(\psi)]^2}{f(\psi)}$$

$$+\frac{\rho(1-\alpha-\beta)(1-\tau_w)}{\theta(1+\tau_c)}\left[\frac{\psi+\sigma\alpha^2 f(\psi)}{f(\psi)}\right]$$

$$>\rho\sigma\alpha^3(1-\alpha)(1+\sigma)\left(\frac{s_n}{1-s_n}\right) \tag{54}$$

Under (26), the left-hand side of inequality (54) is increasing in ψ. Hence, it will be true for any ψ if it is true at $\psi = 0$. At $\psi = 0$, inequality (54) holds if condition (27) holds. Under (28), $\Omega(\psi) < 0$ at $\psi = 0$. Since the left-hand side of (33) is the 45 degree line, (26), (27) and (28) jointly ensure the existence of a unique positive solution for ψ.

A.4. The optimality conditions for social planner's problem

The current-value Hamiltonian to the social planner's optimization problem is

$$H \equiv \frac{1}{\gamma}[(C_t/L)l_t^\theta G_{ct}^\eta]^\gamma+\xi_K[(1-g_c-g_p)Y_t-C_t-(1+\sigma)A_t n_t]+\xi_A\sigma\lambda A_t n_t$$

$$+\xi_Y\{\{g_p^\beta {A_t}^{1-\alpha-\beta}{K_t}^\alpha[(1-l_t)L]^{1-\alpha}\}^{\frac{1}{1-\beta}}-Y_t\}$$

The optimality conditions are

$$\frac{\partial H}{\partial C_t}=C_t^{\gamma-1}(L^{-1}l_t^\theta G_{ct}^\eta)^\gamma-\xi_K=0, \tag{55}$$

$$\frac{\partial H}{\partial Y_t} = \eta[(C_t/L)l_t^{\theta}g_c^{\eta}]^{\gamma}Y_t^{\eta\gamma-1} + \xi_K(1-g_c-g_p) - \xi_Y = 0, \tag{56}$$

$$\frac{\partial H}{\partial n_t} = A_t[\xi_A\sigma\lambda - \xi_K(1+\sigma)] = 0, \tag{57}$$

$$\frac{\partial H}{\partial l_t} = \theta[(C_t/L)G_{ct}^{\eta}]^{\gamma}l_t^{\theta\gamma-1} - \frac{\xi_Y(1-\alpha)Y_t}{(1-\beta)(1-l_t)} = 0, \tag{58}$$

$$\frac{\partial H}{\partial K_t} = \frac{\alpha}{1-\beta}\xi_Y\{g_p^{\beta}A_t{}^{1-\alpha-\beta}[(1-l_t)L]^{1-\alpha}\}^{\frac{1}{1-\beta}}K_t{}^{\frac{\alpha+\beta-1}{1-\beta}} = \rho\xi_K - \dot{\xi_K}, \tag{59}$$

$$\frac{\partial H}{\partial A_t} = \xi_Y\left(\frac{1-\alpha-\beta}{1-\beta}\right)\{g_p^{\beta}K_t{}^{\alpha}[(1-l_t)L]^{1-\alpha}\}^{\frac{1}{1-\beta}}A_t{}^{\frac{-\alpha}{1-\beta}} + [\xi_A\sigma\lambda - \xi_K(1+\sigma)]n_t$$

$$= \rho\xi_A - \dot{\xi_A} \tag{60}$$

$$\lim_{t\to\infty} e^{-\rho t}\xi_K K_t = 0, \tag{61}$$

(1), (34) and (35), where (61) is a transversality condition.

A.5. Derivation of Proposition 2

The growth rate in the decentralized economy will coincide with that in the centrally planned economy if and only if

$$\frac{\alpha^2(1-\tau_k)}{1-s_k} = \frac{\alpha}{1-\beta}\left[1-g_c-g_p+\eta\left(\frac{C_t}{Y_t}\right)\right] \tag{62}$$

Likewise, the consumption leisure margins at the two equilibrium will coincide if and only if

$$(1-\beta)\left(\frac{1-\tau_w}{1+\tau_c}\right) = 1-g_c-g_p+\eta\left(\frac{C_t}{Y_t}\right) \tag{63}$$

When government expenditure is set optimally, i.e., $g_c = g_c^*, g_p = g_p^*$, (62) and (63) reduce to

$$\frac{\alpha(1-\tau_k^*)}{(1-s_k^*)} = 1; \qquad \tau_c^* = -\tau_w^* \tag{64}$$

At the equilibrium under first-best policy, (K_t/A_t) satisfies the condition

$$\frac{K_t}{A_t} = \frac{(1-s_n)\{\rho\sigma\alpha + \{1+\sigma\alpha[1-\gamma(1+\eta)]\}\psi\}}{\sigma\lambda\alpha\{\rho+[1-\gamma(1+\eta)]\psi\}} = \frac{\alpha(1+\sigma)}{\sigma\lambda(1-\alpha-\beta)} \tag{65}$$

Also note that the first-best policy structure should be consistent with government budget constraint (15). We treat g_T^* and s_k^* as exogenously given. By equalizing decentralized solutions and social planner's solutions, we have the following equations which characterize g_c^*, s_n^*, τ_c^* and τ_w^*.

$$g_c^* = \frac{\eta(1-\alpha)}{\theta}\left\{\beta^{\frac{\beta}{1-\alpha}}\left[\frac{\sigma\lambda(1-\alpha-\beta)}{\alpha(1+\sigma)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}} F(g_c^*)^{\frac{\beta-1}{1-\alpha}}-1\right\} \tag{66}$$

$$s_n^* = 1-\frac{\alpha(1-\alpha)(1+\sigma)}{(1-\alpha-\beta)\{1+\sigma\alpha-(1+\eta)g_c^*/[\eta(1-\beta)]\}} \tag{67}$$

$$\tau_c^* = -\tau_w^* = \frac{(1-s_k^*)\left[\alpha+\beta-\alpha^2+g_c^*+\alpha(1+\sigma)s_n^*\left(\frac{1-\alpha}{1-s_n^*}-\frac{1-\alpha-\beta}{1+\sigma}\right)\right]-g_T^*}{(g_c^*/\eta)-(1-\alpha)}-s_k^*$$

where $F(g_c^*)$ is defined in Proposition 2.

Next we show that the first-best policy exists if

$$\frac{\rho}{\alpha\gamma(1+\eta)}<0 \tag{68}$$

$$\beta^{\frac{\beta}{1-\alpha}}\left[\frac{\sigma\lambda(1-\alpha-\beta)}{\alpha(1+\sigma)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}}\left[\frac{\rho}{\alpha\gamma(1+\eta)}\right]^{\frac{\beta-1}{1-\alpha}}>1 \tag{69}$$

For convenience, we define the left-hand side of (66) as LHS and its right-hand side as RHS. We also define $\delta_1 \equiv -\gamma\eta(1-\beta)/[1-\gamma(1+\eta)]$. Note that $\delta_1 \in (0,1)$.

The first-best policy $(g_c^*, g_p^*, g_T^*, \tau_c^*, \tau_w^*, \tau_k^*, s_n^*, s_k^*)$ exists if there is a unique $g_c^* \in (0,1)$. To do so, it suffices to show that there exists a unique $g_c^* \in (0,\delta_1)$ that supports the first-best policy.

To ensure a feasible s_n^*(i.e. $s_n^*<1$) requires $g_c^* < \eta(1-\beta)(1+\sigma\alpha)/(1+\eta)$. This can be readily satisfied for $\forall g_c \in (0,\delta_1)$ since we can verify that $\delta_1 < \eta(1-\beta)(1+\sigma\alpha)/(1+\eta)$. For $g_c \in (0,\delta_1)$, the first order derivatives of $F(g_c)$ and RHS are

$$\frac{\partial F}{\partial g_c} = \frac{-\rho\eta(1-\beta)[1-\gamma(1+\eta)]}{\alpha(1+\eta)\{\gamma\eta(1-\beta)+[1-\gamma(1+\eta)]g_c\}^2}<0$$

$$\frac{\partial RHS}{\partial g_c} = -\frac{\eta(1-\beta)}{\theta}\beta^{\frac{\beta}{1-\alpha}}\left[\frac{\sigma\lambda(1-\alpha-\beta)}{\alpha(1+\sigma)}\right]^{\frac{1-\alpha-\beta}{1-\alpha}} F(g_c)^{\frac{\alpha+\beta-2}{1-\alpha}}\frac{\partial F}{\partial g_c}$$

Since $\partial F/\partial g_c^* < 0$ and $F(0) = \rho/[\alpha\gamma(1+\eta)] < 0$, we have $F(g_c) < 0$ for $\forall g_c \in (0, \delta_1)$. Recall inequality (69) which implies $\{\rho/[\alpha\gamma(1+\eta)]\}^{\frac{\beta-1}{1-\alpha}} > 0$, we have $F(g_c)^{\frac{\beta-1}{1-\alpha}} > 0$ for any $\forall g_c \in (0, \delta_1)$. Hence, $\partial RHS/\partial g_c < 0$ for $\forall g_c \in (0, \delta_1)$. Therefore, under inequalities (68) and (69), RHS is continuous and monotonically decreasing in g_c and $RHS > 0$ at $g_c = 0$. Furthermore, $\lim_{g_c \to \delta_1} RHS = -\eta(1-\alpha)/\theta < 0$. Since LHS is the 45 degree line, it follows that a unique solution for g_c^* exists.

A.6. Derivation of Proposition 3

From (67), $s_n^* \gtreqless 0$ if $g_c^* \lesseqgtr \delta_2$ where $\delta_2 \equiv \eta(1-\beta)(1+\eta)^{-1}[1+\sigma\alpha-\alpha(1-\alpha)(1+\sigma)(1-\alpha-\beta)^{-1}]$. Hence, it follows that $s_n^* > 0$ if $\delta_1 < \delta_2$. If $\delta_1 > \delta_2$, given the monotonicity of RHS, a positive solution for s_n^* exists if $RHS < 1$ at $g_c = \delta_2$. Likewise, a negative solution for s_n^* exists if and only if $RHS > 1$ at $g_c = \delta_2$. $s_n^* = 0$ is also a possibility if $RHS = 1$ at $g_c = \delta_2$.

Table 1

Comparisons among different tax mix

Parameters: $\alpha = 0.3$, $\beta = 0.08$, $\gamma = -1$, $\rho = 0.05$, $\theta = 0.3$, $\eta = 0.3$
$\lambda = 0.5$, $\sigma = 0.1$, $g_c = 0.14$, $g_p = 0.08$, $g_T = 0$

Case 1: $s_k = s_n = 0$

Schemes	τ_c	τ_w	τ_k	s_k	s_n	welfare
τ_c only	0.314	0.000	0.000	0.000	0.000	-191.0
τ_w only	0.000	0.388	0.000	0.000	0.000	-192.5
τ_k only	0.000	0.000	0.413	0.000	0.000	-193.3
τ_w and τ_k	0.000	0.194	0.937	0.000	0.000	-200.2

Case 2: $\tau_w = \tau_k \neq 0$, $s_k = s_n = 0$

Schemes	τ_c	τ_w	τ_k	s_k	s_n	welfare
Tax mix 1	0.318	0.050	0.050	0.000	0.000	-182.3
Tax mix 2	0.248	0.100	0.100	0.000	0.000	-172.3
Tax mix 3	0.178	0.150	0.150	0.000	0.000	-162.3
Tax mix 4	0.109	0.200	0.200	0.000	0.000	-152.4
Tax mix 5	0.039	0.250	0.250	0.000	0.000	-142.7

Case 3:$s_k \neq 0$, $s_n = 0$, $\tau_k = \tau_w = 0.25$

Schemes	τ_c	τ_w	τ_k	s_k	s_n	welfare
Tax mix 1	0.03945	0.250	0.250	0.010	0.000	-142.5351
Tax mix 2	0.03947	0.250	0.250	0.020	0.000	-142.5257
Tax mix 3	0.03948	0.250	0.250	0.030	0.000	-142.5241
Tax mix 4	0.03950	0.250	0.250	0.040	0.000	-142.5218

Case 4: $s_k = 0$, $s_n \neq 0$, $\tau_w = \tau_k = 0.25$

Schemes	τ_c	τ_w	τ_k	s_k	s_n	welfare
Tax mix 1	0.03943	0.25	0.25	0.000	0.050	-141.3107
Tax mix 2	0.04038	0.25	0.25	0.000	0.100	-140.1152
Tax mix 3	0.04246	0.25	0.25	0.000	0.150	-139.1350
Tax mix 4	0.04595	0.25	0.25	0.000	0.200	-138.4145

Table 2

Comparisons among different solutions

Case 1: $\beta = 0.08$, $\gamma = -1$, $\rho = 0.05$, $\theta = 0.3$, $\eta = 0.3$
$\lambda = 0.5$, $\sigma = 0.1$, $g_c = 0.14$, $g_p = 0.08$, $g_T = 0$, $\tau_w = \tau_k = 0.25$, $s_n = 0$

α	τ_c	τ_w	τ_k	s_k	s_n	welfare
0.20	0.03948	0.250	0.250	0.0115	0.000	-142.5391
0.25	0.03946	0.250	0.250	0.0107	0.000	-142.5369
0.35	0.03942	0.250	0.250	0.0101	0.000	-142.5337
0.40	0.03937	0.250	0.250	0.0964	0.000	-142.5311

Case 2: $\beta = 0.08$, $\gamma = -1$, $\rho = 0.05$, $\theta = 0.3$, $\eta = 0.3$
$\lambda = 0.5$, $\sigma = 0.1$,$g_c = 0.14$, $g_p = 0.08$, $g_T = 0$, $\tau_w = \tau_k = 0.25$, $s_k = 0$

α	τ_c	τ_w	τ_k	s_k	s_n	welfare
0.20	0.03981	0.250	0.250	0.000	0.077	-142.9241
0.25	0.03956	0.250	0.250	0.000	0.063	-142.1377
0.35	0.03906	0.250	0.250	0.000	0.037	-140.6415
0.40	0.03883	0.250	0.250	0.000	0.025	-139.8517

Case 3: $\alpha = 0.3$, $\beta = 0.08$, $\gamma = -1$, $\rho = 0.05$, $\theta = 0.3$, $\eta = 0.3$
$\lambda = 0.5$, $g_c = 0.14$, $g_p = 0.08$, $g_T = 0$, $\tau_w = \tau_k = 0.25$, $s_k = 0$

σ	τ_c	τ_w	τ_k	s_k	s_n	welfare
0.2	0.03846	0.250	0.250	0.000	0.046	-141.335
0.3	0.03795	0.250	0.250	0.000	0.031	-140.330
0.4	0.03643	0.250	0.250	0.000	0.018	-139.329
0.5	0.03538	0.250	0.250	0.000	0.007	-138.326