OPTIMAL INCOME TAXATION WITHOUT TAX EVASION

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Abstract: Corruption in the tax administration opens up for tax evasion. This paper is the first to integrate such corruption in a Mirrleesian model of optimal redistributive taxation. We use a multi-type model with a discrete ability distribution to characterize the optimal marginal tax structure. The marginal income tax rates are all non-negative and can be expressed in terms of two key determinants: the distributional weights attached to taxpayers, and how the private cost to evade taxes varies with the taxpayers' income. There is no tax evasion at the second-best optimum. We also consider the role of government expenditures directly targeting the incentives of the tax collector.

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1. Introduction

Tax evasion is a serious problem that undermines redistribution policies and reduces the funds available for public services. Although its magnitude varies among countries, it seems, nevertheless, to be present everywhere. For instance, Pissarides and Weber (1989) estimate that unreported incomes correspond to roughly 5.5 percent of GDP in Britain, which is a considerable number, and in Sweden the National Tax Agency estimates the "tax gap" to be around 8-9 percent of tax revenues. Based largely on the seminal contribution of Allingham and Sandmo (1972), and the extension of their analysis by Yitzhaki (1974), there is now a large literature dealing with the nature, determinants, and implications of tax evasion. This literature focuses on, among other things, the roles of marginal taxation for the incentives to evade (e.g., Clothfelter, 1983; Crane and Nourzad, 1990), auditing (e.g., Beron, Tauchen, and Witte, 1992; Blumenthal, Christian, and Slemrod, 2001), and the potential corruption among tax collectors (e.g., Besley and Mclaren, 1993).[1] The present study deals with the implications of tax evasion for optimal redistributive taxation and, in particular, how an optimal nonlinear income tax ought to respond to corruption in the tax administration. Our approach will be explained and motivated in greater detail below.

A central restriction in the study of optimal redistributive taxation refers to information: in the Mirrleesian (1971) model, productivity and actions are private information, whereas income is observable at the individual level. This rules out type-specific lump-sum taxes (and thus the first-best resource allocation) while allowing for nonlinear taxation of income. Tax evasion reinforces the information problem in the sense that income is no longer fully observable at the individual level, i.e., there is a distinction between the actual and the reported income.

There are two main approaches to tax evasion in the literature on redistributive taxation: one in which tax evasion can be detected through costly auditing, and the other where the evader can avoid detection by incurring a cost. To our knowledge, Cremer and Gahvari (1996) were the first to introduce tax evasion in a two-type version of the Mirrleesian model. Their approach is to examine the optimal mix of nonlinear income taxation and nonlinear penalties, and the results suggest that high-ability individuals should never be audited and should face a zero marginal income tax, while low-ability individuals should be audited with a probability less than one and should either face a positive or zero marginal income tax. Schroyen (1997) examines a similar problem, albeit with a linear (and predetermined) penalty function, and derives results on marginal income taxation

[1] See also the literature reviews by Slemrod (2007, 2019)

that are qualitatively similar to those of Cremer and Gahvari. Chander and Wilde (1998) extend the analysis to a continuum of taxpayers, where the government is unable to observe income at the individual level without costly auditing. Their study provides a general characterization of the income tax schedule, auditing, and enforcement policy, and they find, among other things, a regressive tax structure with non-increasing average tax rates.

Gahvari and Micheletto (2020) analyze the implications of tax evasion for optimal general income taxation in an economy where the before-tax wage rates are endogenous. Their study is based on the riskless approach to tax evasion introduced by Usher (1986), in which a tax evader can avoid detection by incurring a cost that depends on the amout of income misreported. Gahvari and Micheletto find that tax evasion leads to a modification of the policy rule for marginal income taxation through the mechanism associated with endogenous before-tax wage rates. More specifically, the possibility of tax evasion weakens the policy incentive to modify the marginal income tax rates in response to wage endogeneity. The intuition is that tax evasion makes income taxation a less effective instrument for influencing the labor supply behavior. Canta et al. (2024) analyze optimal income taxation in a two-type setting where the private cost of misreporting income is positively correlated with productivity. Their results show that if high-ability individuals report their income truthfully, allowing low-ability individuals to misreport their income may lead to a Pareto-improvement (compared to the outcome if low-ability agents report truthfully).

Yet, none of the studies referred to above focuses on corruption in the tax administration and its implications for optimal redistributive taxation, which is the key issue of the present study. According to Klitgaard (1985), there are different means of corruption in the tax administration; in particular, payments for speeding up the administration of a particular errand, and bribing tax collectors to approve a lower tax payment. Whereas the former typically involves relatively small amounts of money, the latter can be substantial. Klitgaard exemplifies with the Phillipines, where the government estimates that without the latter type of corruption, tax revenues would be 50 percent higher, ceteris paribus. “If a tax examiner discovered these errors [too many deductions, understated income, or incorrect tax computations], he would bring them to the taxpayer’s attention. At this point the arrangement frequently occurred. Typically, the taxpayer paid half of the extra taxes he owed and kept the other half. On the other half, perhaps two-thirds was a bribe to the tax examiner and the other third was paid where it should have been, to the government coffers." (Klitgaard, 1985, p6). This suggests that corruption in the tax administration and, in particular, when it comes to tax collection can be very costly.

To our knowledge, our study is the first to integrate corruption with respect to tax collection in a Mirrlesian (1971) model of optimal taxation. In doing so, we use a discrete formulation of optimal tax problem. The model comprises three agent-types: individuals (or taxpayers), a tax collector (referred to as the "taxman"), and a government. Productivity is private information, and the government wants to redistribute from individuals with high productivity to individuals with lower productivity. However, contrary to standard models of optimal taxation, we assume that individual income is not directly observable to the government, while it is verifiable to the (more or less corrupt) taxman. Thus, there are two ways for any individual to mimic the tax payment of individuals with lower incomes: either by reducing their labor supply in order to reach this particular individual's before-tax income, as in conventional models of optimal redistributive taxation, or by bribing the taxman such that the tax payment corresponds to this level of income. Since the implications for optimal taxation of the former option are well-known, we focus primarily on the latter option and how the government can design a tax system satisfying incentive compatibility. In other words, there is no tax evasion at the second-best optimum.

The model is presented in Section 2, where we describe the objectives and constraints facing the (curruptible) taxman and the taxpayers, respectively, and characterize their choices. Section 3 presents the public decision-problem as well as characterizes the optimal marginal tax structure. We show that the marginal income tax is always non-negative and can be expressed in terms of two key determinants: (i) the government's preferences for redistribution, and (ii) how a change in the taxpayers' income affects the private cost of evading taxes.

Although the second-best optimum characterized in Section 3 implies truthful income reporting, it is not necessarily optimal to induce this behavior solely through the tax system. In Section 4, therefore, we extend the analysis by allowing the government to directly affect the salary of the taxman through public expenditures. This means that the optimal tax structure and the public expenditure to avoid corruption are implemented simultaneously. The results show how the marginal income tax structure depends on the cost of tax evasion facing taxpayers which, in turn, depends on the amount potentially evaded, and on the public expenditures used to incentivize the tax administration. Finally, conclusions are provided in Section 5, while background calculations and proofs can be found in the Online Appendix.

2. The Model

We consider a model with three types of agents: taxpayers, a taxman, and the government. We assume that the taxpayers' true incomes are not observable to either the government or the taxman but can be verified by the taxman through auditing. The taxman's duty is to audit the taxpayers' reported incomes and report their true incomes to the government so that the corresponding taxes (or transfers) can be imposed. A taxpayer chooses their consumption, labor supply, and whether to report their true income and pay the correct amount of tax or to misreport their income and bribe the taxman in exchange for the illicit service of approving their misreported income without auditing. In the latter case, the taxpayer usually reports an income lower than taxpayer's true income, resulting in a lower tax payment.

2.1. **The Taxman.** This subsection examines conditions under which the taxman accepts bribes and the potential size of these bribes. Let y denote the taxpayer's true income and Y the income resported to the taxman. The taxman receives a salary $I_0 > 0$ and is assigned the duty of auditing taxpayers' reported incomes and reporting their true incomes to the government.

There are two important dimensions of corruption in the tax administration, both of which are captured by our model. One is the binary choice of whether or not to engage in corruption: the taxman is either corrupt or not corrupt (see e.g., Amir and Burr, 2015; Banerjee, Mullainathan, and Hanna, 2012). For each taxpayer, the taxman can take one of two possible actions: either audit and truthfully report the taxpayer's true income, $Y = y$, or report the taxpayer's misreported income without auditing, $Y < y$. For the taxman to turn a blind eye to the misreported income, a monetary incentive $B > 0$ is required. This is what we understand as a "bribe".

The other dimension refers to the degree of tax evasion, i.e., the extent to which a taxpayer's income is misreported, which plays a significant role in determining the size of bribe. We assume that without auditing, the taxman has a theoretical continuous distribution of taxpayers' true income y with cumulative distribution $F_y(Y) = P(y \leq Y)$, which has a compact support $[\bar{Y}, \underline{Y}] \subset R$. Then, $1 - F_y(Y)$ represents the probability that taxpayers' true income y is higher than the reported value Y. We also assume that if the taxman decides to audit, then this implies that the taxman will report the taxpayer's true income to the government. Without auditing, on the other hand, a low reported income indicates that the taxpayer's true income could be higher than the reported income and, therefore, the extent to which a taxpayer's income might be misreported.

We will interpret the probability $p = 1 - F_y(Y) \in [0,1]$ to reflect the degree of tax evasion. $p = 0$ implies that the taxman audits the taxpayer's reported income so that the probability that the taxpayer's true income is higher than the reported income is zero. The choice of action by the taxman is governed by a utility function that depends on the degree of tax evasion, p, as well as on the taxman's own income, I: $v(p, I)$, which is decreasing in p, increasing in I, and strictly quasi-concave. In particular, reporting the taxpayer's misreported income to the government without auditing entails a utility cost to the taxman, i.e., $\forall p > 0$, $v(p, I_0) < v(0, I_0)$, where $v(0, I_0)$ represents the officer's utility of receiving salary I_0 and auditing to report the taxpayer's income honestly, i.e., $y = Y$. Intuitively, a more serious degree of tax evasion (i.e., a more serious breach of the taxman's duty) decreases taxman's utility. The simplest justification for our assumption is that more severe misreporting entails a higher risk of detection and punishment, or a decline in professional ethics due to the recognition that misbehavior results in tax revenue loss.[2] We also assume that $\partial^2 v/\partial I \partial p \leq 0$, such that the marginal utility of income (weakly) declines in the degree of tax evasion.

In order to report income $Y < y$ without auditing, the bribe $B > 0$ acceptable to the taxman, who receives the salary I_0 must satisfy:

$$u(p, B + I_0) \geq v(0, I_0). \tag{1}$$

It follows that the reservation bribe is given by $B(p, I_0)$ such that[3]

$$u(p, I_0 + B(p, I_0)) \equiv v(0, I_0). \tag{2}$$

Here, the reservation bribe $B(p, I_0)$ depends on the taxpayer's reported income Y, and the salary I_0.

Since $p = 1 - F_y(Y)$, the utility of the taxman can also be defined on the support of the income distribution such that $u(Y, I) \equiv v(p, I)$. Obviously, $u(Y, I)$ is increasing in each argument. When the reported income Y increases, and in the absence of auditing, the probability that the taxpayer's true income is higher than the reported income decreases and the potential difference between the true income and the reported income decreases as well, implying that the taxman's utility increases. The reservation bribe given by equation (2) can be rewritten as $B(Y, I_0)$, depending on

[2]We do not explicitly model the probability that the taxman faces legal sanctions, but the analysis can easily be extended along those lines.

[3]Note that we have taken the point of view that a bribe is a perfect substitute for salary income. In case one wishes to capture the idea of moral inhibitions about receiving bribes, this can be incorporated by a suitable adjustment instead of adding the two sources of monetary payoff.

the taxpayer's reported income Y, and the salary I_0.[4] The reservation bribe function satisfies the following comparative statics property with respect to Y:

$$\frac{\partial B(Y,I_0)}{\partial Y} = -\frac{\partial u/\partial Y}{\partial u/\partial I} = \frac{\partial v/\partial p \times F_y'(Y)}{\partial v/\partial I} < 0. \tag{3}$$

We can similarly derive the following comparative statics with respect to I_0:[5]

$$\begin{aligned}\frac{\partial B(Y,I_0)}{\partial I_0} &= \frac{\partial v(0,I_0)/\partial I - \partial u(Y,I_0+B)/\partial I}{\partial u(Y,I_0+B)/\partial I} \\ &= \frac{\partial v(0,I_0)/\partial I}{\partial v(Y,I_0+B)/\partial I} - 1 \geq 0.\end{aligned} \tag{4}$$

2.2. **The Taxpayers.** We have $N = \{1,...n\}$ types of taxpayers who differ in ability but have the same utility function. Each type i, where $i = 1,...n$, faces a before-tax wage rate per unit of labor of $w_i \in W = \{w_1,...w_n\}$. We assume that the levels of ability represented by the before-tax wage rates are totally ordered. Let C_i and L_i denote the consumption and labor supply, respectively, of an individual of any type i. The ability (productivity) of the taxpayer is private information, and the labor supply is not observable. In addition to these standard assumptions, we assume that the before-tax income, $Y_i = w_i L_i$, is not directly observable to the government but verifiable to the taxman by auditing.

Each taxpayer derives utility from consumption and disutility from labor/effort. By using $L_i = Y_i/w_i$, the utility function of a taxpayer of any type i can be written as follows:

$$U^i = U(C_i, \frac{Y_i}{w_i}) \equiv V^i(C_i, Y_i), \tag{5}$$

which is increasing in C_i, decreasing in Y_i for a given before-tax wage rate, and strictly quasi-concave. Superscript i on the function $V^i(\cdot,\cdot)$ indicates that utility varies with the before-tax wage rate for given levels of the before-tax income and consumption. We also assume that the indifference curves in income-consumption space become flatter when the before-tax wage rate increases, i.e., $-\partial(V^i_{Y_i}/V^i_{C_i})/\partial w_i < 0$, where subscripts attached to the utility function denote partial derivatives. If individuals report their income truthfully, this condition ensures that the before-tax income and the consumption both increase monotonically in ability, in which case interior bunching is ruled out.

[4]Another way of modeling the degree of tax evasion is to measure it as the difference between the taxpayer's true income and the reported income, i.e., $y - Y$. Such a change of the model would not influence the qualitative results presented below. Possible extensions, such as bargaining between the taxman and taxpayers regarding the value of the bribe or extortion where the tax inspector can report or threaten to report a taxable income higher than the true amount, as in Hindriks et al. (1999), are not the focus of this paper.

[5]Note that $v(p, I)$ is increasing and concave in I, p is decreasing in Y, and $\partial^2 v/\partial I \partial p \leq 0 \implies \partial v(0, I_0 + B)/\partial I \geq \partial v(p, I_0 + B)/\partial I$. We obtain $\partial v(0, I_0)/\partial I \geq \partial v(Y, I_0 + B)/\partial I$.

Suppose that the government imposes a tax as a function of the income reported by the taxman. *In the absence of tax evasion*, the reported income is, of course, the taxpayer's true income. The tax imposed on a taxpayer with income Y_i is defined as $T_i = T(Y_i)$, which can be either positive or negative, while the consumption is given by the taxpayer's income minus the tax payment

$$C_i = Y_i - T(Y_i). \tag{6}$$

In the absence of any tax evasion, the utility maximization problem facing the taxpayer can be written as

$$\max_{C_i, Y_i} V^i(C_i, Y_i), s.t., C_i \leq Y_i - T(Y_i), \tag{7}$$

yielding the first-order condition

$$V^i_{Y_i}/V^i_{C_i} + 1 = T^{'}(Y_i), \tag{8}$$

where $T^{'}(Y_i)$ is the marginal income tax rate.

Tax evasion means that a taxpayer can pay a bribe in order to evade taxes. Specifically, a taxpayer of any type i can pay the bribe $B(Y_j, I_0)$ in exchange for the illicit service provided by the taxman to report income Y_j instead of Y_i to the government, where $Y_j < Y_i$ and Y_j is the income of type $j \in N$. A taxpayer of type i who pays the bribe $B(Y_j, I_0)$ and is imposed the tax payment $T(Y_j)$ thus solves

$$\begin{aligned} &\max_{C_i, Y_i} V^i(C_i, Y_i), \\ &\text{s.t.} C_i \leq Y_i - T(Y_j) - B(Y_j, I_0). \end{aligned} \tag{9}$$

where $T(Y_j) = Y_j - C_j$, $i, j \in N$, $j \neq i$. The first-order condition of the problem (9) can be written as

$$V^i_{Y_i} + V^i_{C_i} = 0. \tag{10}$$

Let $\bar{C}_i(C_j, Y_j)$, and $\bar{Y}_i(C_j, Y_j)$ be the solution to problem (9). Clearly, since the tax payment and the reservation bribe are both determined by the income of taxpayers of type j, the utility of a taxpayer of type i, evaluated at the optimum choice $(\bar{C}_i, \bar{Y}_i)$, can be rewritten as a function of (C_j, Y_j). We use $\bar{V}^i(C_j, Y_j) \equiv V^i(\bar{C}_i(C_j, Y_j), \bar{Y}_i(C_j, Y_j))$ to denote the maximum utility associated with such tax evasion. By the Envelope Theorem, we obtain

$$\bar{V}^i_{C_j} = V^i_{\bar{C}_i} > 0. \tag{11}$$

$$\bar{V}^i_{Y_j} = -V^i_{\bar{C}_i}(1 + \partial B_j/\partial Y_j). \tag{12}$$

As the consumption (or disposable income) of type j increases, the maximum utility that type i can achieve by mimicking type j through tax evasion increases as well. Similarly, a higher before-tax income of type j has a positive effect, $-V^i_{\hat{C}_i} \cdot \frac{\partial B_j}{\partial Y_j}$, and a negative effect, $-V^i_{\hat{C}_i}$, on the maximum utility the type i evader can achieve.[6] Therefore, the overall effect of Y_j on the maximized utility of the type i mimicker is ambiguous.

We will begin with a purely redistributive tax system, which does not raise any net tax revenue for public consumption. A more general version of the model will be examined in Section 4, where the government also uses public expenditures to fight corruption by incentivizing the taxman. This case means that the government alleviates corruption both through the tax system and via public expenditures.

3. The Optimal Marginal Tax Structure

We focus on the optimal marginal tax structure in a normal case, where redistribution favors people with lower earnings ability (productivity). This means that people with higher earnings ability are the ones who would potentially evade taxes and can afford the costs to evade taxes as well.[7] Tax evasion arises in our model if the taxman accepts the bribe offered by a taxpayer and untruthfully reports the taxpayer's income.

Note that in our framework, and in the absence of any concerns for incentive compatibility, higher-ability individuals could potentially mimic the lower-ability types either through adjustments of their labor supply (in order to reach the same before-tax income as the lower-ability type) or through tax evasion by bribing the taxman (allowing them to pay the same tax as the lower-ability type even though their before-tax income is higher). Thus, there are two categories of self-selection constraints: one category serves to prevent each taxpayer from mimicking taxpayers of lower ability through tax evasion, while the other serves to prevent mimicking through labor supply adjustments.

The government maximizes a social welfare function by offering n packages of private consumption and labor/effort, i.e., $\{C, Y\}$ in which $\{C_i, Y_i\}$ will be chosen for individuals of type i. The

[6] Recall that $V^i_{\hat{C}_i} > 0$ and $\frac{\partial B_j}{\partial Y_j} < 0$.

[7] Alstadsæter, Johannesen and Zucman (2019) find that the 0.01 percent richest households in Scandinavia evade about 25 percent of their taxes. Leenders, et al. (2023) document that in the Netherlands, top 0.01 percent evade around 8 percent of their true tax liability, and that there is substantial evasion among the "merely rich" (90 percent - 99.9 percent) who own around 67 percent of the hidden wealth.

social decision-problem can then be written as[8]

$$
\begin{aligned}
&\max_{C_1,...C_n,Y_1,...Y_n} \sum_{i=1}^{n} \beta_i N_i V^i(C_i, Y_i),\\
&\text{s.t.} V^n(C_n, Y_n) \geq \bar{V}^n(C_{n-1}, Y_{n-1}),\\
&V^n(C_n, Y_n) \geq V^n(C_{n-1}, Y_{n-1}),\\
&...\\
&V^n(C_n, Y_n) \geq \bar{V}^n(C_1, Y_1),\\
&V^n(C_n, Y_n) \geq V^n(C_1, Y_1),\\
&V^{n-1}(C_{n-1}, Y_{n-1}) \geq \bar{V}^{n-1}(C_{n-2}, Y_{n-2}),\\
&...\\
&V^2(C_2, Y_2) \geq \bar{V}^2(C_1, Y_1),\\
&V^2(C_2, Y_2) \geq V^2(C_1, Y_1),\\
&\sum_{i=1}^{n}(Y_i - C_i)N_i = 0,
\end{aligned}
\tag{13}
$$

where N_i is the number of taxpayers of type i, $i = 1, ...n$. The parameter β_i reflect the weight the government attaches to the utility of type i, and we assume that these weight reflect the redistribution profile discussed above. The resource constraint (the final constraint in (13)) means that aggregate income (or output) is equal to aggregate private consumption.

It is important to emphasize that both two categories of self-selection constraints cannot bind simultaneously, except in the unlikely case where both types of mimicking give rise to exactly the same utility for the potential mimicker. Intuitively, if a high-ability individual reduces their labor supply in order to mimic the before-tax income of an individual with lower earnings ability, there would be no incentives for this individual to pay a positive bribe. Similarly, if the maximized utility of tax mimicking through evasion is greater than the utility of mimicking through labor supply adjustments, there would be no incentive to undertake such adjustments.

Since the implications of preventing mimicking through labor supply adjustments are wellknown from earlier research, this paper focuses on the case in which "tax mimicking" by bribing the taxman is more desirable for the taxpayers, i.e., the case where the first category of self-selection

[8]Since individuals with lower earnings ability pay lower taxes than individuals with higher earnings ability, low-ability individuals cannot evade taxes by mimicking high-ability individuals, i.e., a self-selection constraint imposed to prevent such mimicking would not bind. For a similar reason, a self-selection constraint designed to prevent mimicking upwards through labor supply adjustments would not bind either.

constraints in problem (13) is dominating. The Lagrangean corresponding to problem (13) can then be written as follows:

$$
\begin{aligned}
\mathcal{L} = & \sum_{i=1}^{n} \beta_i N_i V^i(C_i, Y_i) \\
& + \sum_{j=1}^{n-1} \lambda_{n,j} [V^n(C_n, Y_n) - \bar{V}^n(C_j, Y_j)] \\
& ... \\
& + \sum_{j=1}^{i-1} \lambda_{i,j} [V^i(C_i, Y_i) - \bar{V}^i(C_j, Y_j)] \\
& ... \\
& + \gamma \sum_{i=1}^{n} (Y_i - C_i) N_i,
\end{aligned}
\tag{14}
$$

where $j \in \mathbb{N}$. $\lambda_{i,j}$ denotes the Lagrange multiplier on the self-selection constraint that serves to prevent type i from mimicking type j through tax evasion. The social first-order conditions are presented in the Appendix.

Before characterizing the policy rules for marginal income taxation, note that taxpayers of type n could in principle mimic any of the $n-1$ types with lower ability. Similarly, taxpayers of type $n-1$ could in principle mimic any of the $n-2$ types with lower ability, and so on. In such a framework, it is not obvious which self-selection constraint that is binding for a given type at the social optimum. We will, therefore, begin with a general characterization, which applies regardless of the structure of binding self-selection constraints. Consider Proposition 1.

Proposition 1. *The optimal marginal tax structure that prevents tax evasion satisfies* $T'(Y_n) = 0$ *and*

$$
T'(Y_j) = -\frac{\sum_{i=j+1}^{n} \lambda_{i,j} \bar{V}^i_{C_j} / \gamma N_j}{1 + \sum_{i=j+1}^{n} \lambda_{i,j} \bar{V}^i_{C_j} / \gamma N_j} \frac{\partial B_j}{\partial Y_j} \geq 0
\tag{15}
$$

for $j = 1, ..., n-1$.

Proposition 1 shows that if the government attempts to redistribute from high-ability to low-ability individuals, and at the same time prevent any tax evasion, the optimal tax policy includes non-negative marginal income tax rates at all income levels.

The right-hand side of equation (15) just summarizes the effects of all potentially binding self-selection constraints on the marginal income tax rate implemented for taxpayers of any type j. As such, it reflects and neutralizes the incentives of all types higher than j to mimic type j. However, except in the unlikely case where several mimicking-options give rise to exactly the same utility for a potential mimicker, we would expect that only one such constraint binds for each distinct ability-type. The optimal marginal tax structure also captures how the reservation bribe (charaterizing the taxman) reacts to an increase in the before-tax income of the potentially mimicked agent. The intuition is that a lower reported before-tax income leads to an increase in the reservation bribe (see equation (3)), which motivates the government to increase the marginal tax in order to make tax evasion more costly.

Therefore, on the one hand, the government imposes marginal taxation at lower levels of income to avoid tax evasion among people higher up in the income distribution. On the other hand, low-income earners would be secured to benefit from the redistribution achieved by such a tax scheme.

In Corollary 1, we consider two special cases directly following from Proposition 1. In one of these special cases, each individual potentially mimics the adjacent type with lower productivity (which is the conventional assumption in other literature on optimal taxation), and in the other each individual would potentially mimic the type with the lowest productivity.

Corollary 1. *If each individual would potentially mimic the adjacent type with lower productivity, the optimal marginal tax structure in Proposition 1 simplifies to* $T^{'}(Y_n) = 0$ *and*

$$T^{'}(Y_j) = -\frac{\lambda_{j+1,j}\bar{V}^i_{C_j}/\gamma N_j}{1+\lambda_{j+1,j}\bar{V}^i_{C_j}/\gamma N_j}\frac{\partial B_j}{\partial Y_j} > 0 \tag{16}$$

for $j = 1, ..., n-1$. *Instead, if each individual of type* $j > 1$ *would potentially mimic type* 1*, then* $T^{'}(Y_j) = 0$ *for* $j = 2, ..., n$ *and*

$$T^{'}(Y_1) = -\frac{\sum_{i=2}^{n}\lambda_{i,1}\bar{V}^i_{C_1}/\gamma N_1}{1+\sum_{i=2}^{n}\lambda_{i,1}\bar{V}^i_{C_1}/\gamma N_1}\frac{\partial B_1}{\partial Y_1} > 0. \tag{17}$$

Policy rule (16) is designed to prevent individuals of any type $j+1$ to mimic type j through tax evasion. In turn, this motivates marginal taxation of type j's income. Thus, when each individual would potentially mimic the adjacent type with lower productivity, the marginal income taxes are positive along the whole income distribution (except at the very top). Policy rule (17) is more extreme, as it corresponds to the (somewhat unlikely) scenario where all individuals would mimic type 1 in the absence of self-selection constraints preventing such behavior. In this case, therefore, only type 1 would face a positive marginal tax rate (designed to prevent all higher types from mimicking type 1), while the other marginal income tax rates would be zero.

The two special cases in the corollary can be interpreted as polar cases in terms of how sensitive the bribe is to the amount of taxes evaded. If all individuals of abilities higher than type 1 would prefer to potentially mimic this type, i.e., if mimicking type 1 gives higher utility than the other mimicking options, then the effect on the bribe of the amount of taxes evaded is likely to be relatively small. Otherwise, it would be too costly for the highest types (who would need to evade substantial amounts) to prefer this particular option. On the other hand, if the bribe is very sensitive to the amount evaded, a potential mimicker is likely to prefer less evasion, which is exemplified by the case where individuals would mimic the adjacent type with lower ability in the absence of constraints ensuring incentive compatibility.

Returning finally to the general policy rules in Proposition 1, it is straightforward to rewrite the marginal income tax rates in terms of distributional weights, which reflect the social desire to redistribute from individuals with abilities higher than any type j to individuals with abilities lower than or equal to this particular type. In fact, such a policy rule would always apply regardless of which self-selection constraints that bind. Let $\delta_j = \beta j V_{C_j}/\gamma \geq 1$ denote the distributional weight the government attaches to individuals of type j. This weight reflects the marginal social value of consumption relative to the marginal cost of public funds. Corollary 2 below is an immediate consequence of the calculations behind Proposition 1.

Corollary 2. *The policy rules in Proposition 1 can be reformulated to read*

$$T^{'}(Y_j) = \frac{1-\delta_j}{\delta_j}\frac{\partial B_j}{\partial Y_j} \geq 0 \tag{18}$$

for $j = 1, ..., n$.

Note once again that equation (18) is a reformulation of equation (15) in Proposition 1 and, therefore, also consistent with special cases (16) and (17) in Corollary 1. Thus, as long as we can estimate the distributional weights and the functional relationship between income and the reservation bribe, there is no need to assume which self-selection constraint that is actually binding for each type at the social optimum. To interpret Corollary 2, we assume that the welfare weight is declining in consumption. This means that the higher the distributional weight attached to type j, the more the government would like to redistribute income to people with abilities lower than or equal to j, ceteris paribus. To accomplish this redistribution, the government raises revenue from people with abilities higher than j through marginal taxation of type j's income. Given the distributional weight, the second factor determines the level of marginal taxation such that the optimal redistribution does not lead people with abilities higher than j to mimic type j.

4. Public Expenditure to Incentivize the Taxman

In this section, we extend the analysis by including public expenditures directed at anti-corruption efforts. More specifically, the government can now raise net tax revenue in order to increase the salary of the taxman, which provides another channel through which to improve the quality of the tax administration. This is interesting for at least two reasons. First, earlier research shows that the direct incentives facing tax collectors are important for the functioning of the tax administration (e.g., Besley and Mclaren, 1993). In our framework, public expenditures targeting the incentives of the taxman contribute to raise the the cost of tax evasion which, in turn, relaxes the self-selection constraints and opens up for more redistribution. Second, the introduction of direct anti-corruption measures will affect the policy incentives underlying the optimal marginal tax policy.

Let E denote the public expenditure the government uses to incentivize the tax administration; in our case, through the salary of the taxman. We can then rewrite the reservation bribe to read $B(Y, E)$, since the salary of the taxman is now a direct decision-variable of the government. Thus, the reservation bribe is now a function of both the reported income of the taxpayer and the public expenditures targeting the incentives of the tax administration.

The optimization problem facing the true taxpayers, i.e., those who truthfully report their income, is given by problem (7) in Section 2, the solution of which satisfies equation (8). On the other hand, if a taxpayer of any type i were to engage in tax evasion, by reporting a lower before-tax income, this taxpayer now solves a decision-problem that depends directly on E, i.e.,

$$\max_{C_i, Y_i} V^i(C_i, Y_i), s.t. C_i \leq Y_i - (Y_j - C_j) - B(Y_j, E), \tag{19}$$

where $j, i \in \mathbb{N}$ and $j < i$. Recall that individuals of any type $i > 1$ could potentially mimic any other type with lower productivity through tax evasion and would in that case choose the option giving the highest utility. The first-order condition of problem (19) is

$$V^i_{C_i} + V^i_{Y_i} = 0. \tag{20}$$

Let $\bar{C}_i(C_j, Y_j, E)$, and $\bar{Y}_i(C_j, Y_j, E)$ be the solution of problem (19), and let $\bar{V}^i(C_j, Y_j, E) \equiv V^i(\bar{C}_i(C_j, Y_j, E), \bar{Y}_i(C_j, Y_j, E))$ denote the corresponding value function. We show in the Appendix that this function satisfies the following comparative statics property with respect to E:

$$\frac{\partial \bar{V}^i(C_j,Y_j,E)}{\partial E} = -\frac{\partial \bar{V}^i(C_j,Y_j,E)}{\partial C_j}\frac{\partial B(Y_j,E)}{\partial E} \leq 0. \tag{21}$$

Thus, by increasing the (publicly funded) salary to the taxman, in order to strengthen the quality of the tax administration, the utility of being a mimicker decreases, ceteris paribus. The intuition is, of course, that this policy increases the reservation bribe at any income level.

The social decision-problem takes the same form as in Section 3 with two important modifications: (i) the public expenditure directed at anti-corruption, E, is now a direct decision-variable of the government/social planner which, in turn, modifies the resource constraint, and (ii) E directly affects all self-selection constraints and thus the incentives underlying tax evasion, since the utility of an individual of any type i mimicking type j now takes the form $\bar{V}^i(C_j,Y_j,E)$. Otherwise, the Lagrangean of the social optimization problem takes the same form as in Section 3 (see the Appendix). Consider Proposition 2.

Proposition 2. *If the government can incentivize the tax administration by choosing the salary of the taxman, the optimal marginal tax structure that prevents tax evasion satisfies* $T^{'}(Y_n,E)=0$ *and*

$$T^{'}(Y_j,E) = -\frac{\sum_{i=j+1}^{n}\lambda_{i,j}\bar{V}^i_{C_j} / \sum_{j=1}^{n-1}\sum_{i=j+1}^{n}\lambda_{i,j}\bar{V}^i_{C_j}\frac{\partial B(Y_j,E)}{\partial E}N_j}{1+\sum_{i=j+1}^{n}\lambda_{i,j}\bar{V}^i_{C_j} / \sum_{j=1}^{n-1}\sum_{i=j+1}^{n}\lambda_{i,j}\bar{V}^i_{C_j}\frac{\partial B(Y_j,E)}{\partial E}N_j}\frac{\partial B(Y_j,E)}{\partial Y_j} \geq 0, \tag{22}$$

for $j=1,...,n-1$.

The right-hand side of the equation (22) is interpretable as the marginal income tax rate implemented for any type j when the optimal tax structure and the public expenditure to avoid corruption in the tax administration are chosen simultaneously. Intuitively, the optimal public expenditure on anti-corruption efforts influences the minimum bribe required by the taxman for a given level of taxpayer income. Therefore, the marginal income tax that neutralizes the incentives of all taxpayers with abilities higher than j to mimic type j through tax evasion takes into account the marginal effects of the government's anti-corruption expenditure on the taxpayers' cost of tax evasion. As explained above, since each potential mimicker would choose the mimicking option giving the highest utility, all these self-selection constraints cannot bind at the same time. It is the best mimicking strategy that the binding self-selection constraint should prevent which, in turn, reflects the realized value of the expression $\sum_{j=1}^{n-1}\sum_{i=j+1}^{n}\lambda_{ij}\bar{V}_{C_j}^{i}\frac{\partial B(Y_j,E)}{\partial E}$.

Let $\Delta_j = \beta j V_{C_j}^{j}/\gamma \geq 1$ denote the distributional weight the government attaches to individuals of type j at the social optimum, where the social first-order condition for E gives the marginal cost of public funds as follows:

$$\gamma = \sum_{j=1}^{n-1}\sum_{i=j+1}^{n}\lambda_{ij}\bar{V}_{C_j}^{i}\frac{\partial B(Y_j,E)}{\partial E}. \tag{23}$$

Corollary 3 below is an immediate consequence of the calculations behind Proposition 2. This corollary is analogous to Corollary 2, with the exception that the marginal cost of public funds now equals the marginal welfare benefit of E.

Corollary 3. *The policy rules in Proposition 2 can be reformulated to read*

$$T^{'}(Y_j,E) = \frac{1-\Delta_j}{\Delta_j}\frac{\partial B(Y_j,E)}{\partial Y_j} \geq 0 \tag{24}$$

for $j = 1, ..., n$.

Therefore, since policy rule (24) is an alternative formulation of policy rule (22), it is also consistent with all special cases of (22), such as potential potential mimicking of the adjacent type with lower ability or the extreme case where all individuals would have mimicked type 1 in the absence of government intervention. Here, where the optimal tax structure and the salary of the taxman are chosen simultaneously, we can see that the distributional weight the government attaches to any type j depends on the effects of E on the reservation bribe. More specifically, the higher the overall marginal effects of the government's anti-corruption expenditure on the reservation bribe, the lower the distributional weight attached to any type j, and vice versa, ceteris paribus. This result was expected: the more efficient the direct anti-corruption effort, the higher the public expenditure directed towards anti-corruption, and the higher will be the marginal tax rates needed to reach the desired redistribution.

5. Summary and Conclusion

This paper develops a Mirrleesian model of optimal redistributive taxation in an economy with potential corruption in the tax administration. In our framework, there are two potential channels for individuals to mimic people with lower income: by reducing their labor supply (as in conventional models of optimal taxation) or by tax evasion accomplished through bribing the tax collector. The latter mechanism is novel in the literature on optimal taxation and also the focus of the present paper. Thus, public sector concerns for incentive compatibility lead the policy maker to design the marginal tax schedule such that tax evasion becomes undesirable for each individual. The contribution of the paper is to characterize the marginal tax schedule and show how this schedule can be designed to avoid tax evasion. In turn, this tax schedule reflects how the discrepancy between the taxpayers' reported and actual income affects the reservation bribe required by the tax collector to misreport individual income, and how public expenditures targeting the incentives of the tax collector affect this bribe. Our characterization is general in the sense of applying regardless of which (out of several possible) self-selection constraints that binds for a given ability-type. The policy rules for marginal income taxation can be expressed in terms of two key variables: the distributional weights attached to individuals, and how sensitive the reservation bribe is to changes in the reported income.

Future research may take several directions. One would be to integrate corruption in the tax administration (which is the focus of our paper) with other possible mechanisms underlying tax evasion such as imperfect monitoring. This would enable us to examine the simultaneous design of marginal income tax schedules and penalty schedules, which is clearly an interesting topic. In addition, to the extent that tax evasion is more common among the wealthy, another relevant extension would be to analyze the policy implications of tax evasion in a dynamic framework with taxes on capital income and/or wealth. We hope to address both these issues in future research.

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OPTIMAL INCOME TAXATION WITHOUT TAX EVASION: ONLINE APPENDIX

Thomas Aronsson and Fei Xu

Proof of Proposition 1:

For type 1, the social first-order conditions for Y_1 and C_1 read

$$\beta_1 N_1 V^1_{Y_1} - \sum_{i=2}^{n} \lambda_{i,1} \bar{V}^i_{Y_1} + \gamma N_1 = 0, \tag{25}$$

$$\beta_1 N_1 V^1_{C_1} - \sum_{i=2}^{n} \lambda_{i,1} \bar{V}^i_{C_1} - \gamma N_1 = 0. \tag{26}$$

Following the same procedure of calculation of two types model, we obtain

$$T^{'}(Y_1) = -\frac{\sum_{i=2}^{n} \lambda_{i,1} \bar{V}^i_{C_1}/\gamma N_1}{1 + \sum_{i=2}^{n} \lambda_{i,1} \bar{V}^i_{C_1}/\gamma N_1} \frac{\partial B_1}{\partial Y_1} > 0. \tag{27}$$

For type 2, since all the type with higher productivity than type 2 would evade tax and potentially mimicking type 2, the social first-order conditions for Y_2 and C_2 read

$$\beta_2 N_2 V^2_{Y_2} - \sum_{i=3}^{n} \lambda_{i,2} \bar{V}^i_{Y_2} + \gamma N_2 = 0, \tag{28}$$

$$\beta_2 N_2 V^2_{C_2} - \sum_{i=3}^{n} \lambda_{i,2} \bar{V}^i_{C_2} - \gamma N_2 = 0. \tag{29}$$

we obtain

$$T^{'}(Y_2) = -\frac{\sum_{i=3}^{n} \lambda_{i,2} \bar{V}^i_{C_2}/\gamma N_2}{1 + \sum_{i=3}^{n} \lambda_{i,2} \bar{V}^i_{C_2}/\gamma N_2} \frac{\partial B_2}{\partial Y_2} > 0. \tag{30}$$

And so on, for type $n-1$, we obtain

$$T^{'}(Y_{n-1}) = -\frac{\lambda_{n,(n-1)} \bar{V}^n_{C_{n-1}}/\gamma N_{n-1}}{1 + \lambda_{n,(n-1)} \bar{V}^n_{C_{n-1}}/\gamma N_{n-1}} \frac{\partial B_{n-1}}{\partial Y_{n-1}} > 0. \tag{31}$$

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There is no other types mimicking type n, we obtain

$$T^{'}(Y_n) = 0. \tag{32}$$

We conclude that for type $j = 1, ..., n-1$,

$$T^{'}(Y_j) = -\frac{\sum_{i=j+1}^{n} \lambda_{i,j} \bar{V}^i_{C_j} / \gamma N_j}{1 + \sum_{i=j+1}^{n} \lambda_{i,j} \bar{V}^i_{C_j} / \gamma N_j} \frac{\partial B_j}{\partial Y_j} > 0 \tag{33}$$

Proof of Corollary 1:

The proof of Corollary 1 immediately follow from Proposition 2 by making the appropriate assumptions about binding self-selection constraints. Specifically, policy rule (16) is obtained by assuming that the best evasion strategy is to mimic the tax payment of the adjacent type with lower productivity, which the binding self-selection constraint serves to prevent. That is, for $i = 2, 3, ...n$, if $j = i - 1$, $\lambda_{i,j} > 0$, otherwise, $\lambda_{i,j} = 0$.

Instead, if each individual of type $j > 1$ would potentially mimic type 1, then we solve the Lagrangean function (14) assuming that for $i = 2, 3, ...n$, $\lambda_{i,1} > 0$, while for any $j \neq 1$, $\lambda_{i,j} = 0$. Hence, the proof of policy rule (17) is obtained.

Proof of Corollary 2:

The social first-order condition of Lagrangean function (14) for C_j can be written as

$$\beta_j N_j V^j_{C_j} - \gamma N_1 = \sum_{i=j+1}^{n} \lambda_{i,j} \bar{V}^i_{C_j}. \tag{34}$$

Substitute equation (34) into equation (15),

$$T^{'}(Y_j) = -\frac{(\beta_j N_j V^j_{C_j} - \gamma N_j)/\gamma N_j}{1 + (\beta_j N_j V^j_{C_j} - \gamma N_j)/\gamma N_j} \frac{\partial B_j}{\partial Y_j}. \tag{35}$$

Rearrangement gives

$$T^{'}(Y_j) = -\frac{\beta_j N_j V^j_{C_j}/\gamma N_j - 1}{\beta_j N_j V^j_{C_j}/\gamma N_j} \frac{\partial B_j}{\partial Y_j}. \tag{36}$$

This can also be written as

$$T^{'}(Y_j) = \left(\frac{1}{\beta_j V^j_{C_j}/\gamma} - 1 \right) \frac{\partial B_j}{\partial Y_j}. \tag{37}$$

Define the social welfare weight attached to type j, $\delta_j = \beta j V_{C_j}/\gamma$, we have

$$T^{'}(Y_j) = \frac{1 - \delta_j}{\delta_j} \frac{\partial B_j}{\partial Y_j} \geq 0. \tag{38}$$

Calculation of Equation (21):

The optimal consumption of the type i satisfies

$$\bar{C}_i(C_j, Y_j, E) \equiv \bar{Y}_i(C_j, Y_j, E) - (Y_j - C_j) - B(Y_j, E). \tag{39}$$

Meanwhile, at the optimal point, the first order condition (20) gives

$$\frac{\partial V^i(\bar{C}_i(C_j, Y_j, E), \bar{Y}_i(C_j, Y_j, E))}{\partial C_i} + \frac{\partial V^i(\bar{C}_i(C_j, Y_j, E), \bar{Y}_i(C_j, Y_j, E))}{\partial Y_i} \equiv 0. \tag{40}$$

Then we obtain

$$\frac{\partial \bar{V}^i(C_j, Y_j, E)}{\partial E} = \frac{\partial V^i(\bar{C}_i, \bar{Y}_i)}{\partial C_i}\frac{\partial \bar{C}_i}{\partial E} + \frac{\partial V^i(\bar{C}_i, \bar{Y}_i)}{\partial Y_i}\frac{\partial \bar{Y}_i}{\partial E}. \tag{41}$$

Since

$$\frac{\partial \bar{C}_i(C_j, Y_j, E)}{\partial E} = \frac{\partial \bar{Y}_i(C_j, Y_j, E)}{\partial E} - \frac{\partial B(Y_j, E)}{\partial E}, \tag{42}$$

by envelop theorem, we obtain

$$\frac{\partial \bar{V}^i(C_j, Y_j, E)}{\partial E} = -\frac{\partial V^i(\bar{C}_i, \bar{Y}_i)}{\partial C_i} \cdot \frac{\partial B(Y_j, E)}{\partial E} \leq 0. \tag{43}$$

Substitute equation (11) into equation (43) could be rewritten as

$$\frac{\partial \bar{V}^i(C_j, Y_j, E)}{\partial E} = -\frac{\partial \bar{V}^i(C_j, Y_j, E)}{\partial C_j} \cdot \frac{\partial B(Y_j, E)}{\partial E} \leq 0. \tag{44}$$

The Lagrangean of the social decision-problem including public expenditures directed at anti-corruption efforts:

$$\begin{aligned}
\mathcal{L} = & \sum_{i=1}^{n} \beta_i N_i V^i(C_i, Y_i) \\
& + \sum_{j=1}^{n-1} \lambda_{n,j}[V^n(C_n, Y_n) - \bar{V}^n(C_j, Y_j, E)] \\
& \cdots \\
& + \sum_{j=1}^{i-1} \lambda_{i,j}[V^i(C_i, Y_i) - \bar{V}^i(C_j, Y_j, E)] \\
& \cdots \\
& + \gamma \left[\sum_{i=1}^{n} (Y_i - C_i) N_i - E \right].
\end{aligned} \tag{45}$$

Proof of Proposition 2:

The social first-order conditions for Y_1, C_1, and E read

$$\beta_1 N_1 V^1_{Y_1} - \sum_{i=2}^{n} \lambda_{i1} \bar{V}^i_{Y_1} + \gamma N_1 = 0, , \tag{46}$$

$$\beta_1 N_1 V^1_{C_1} - \sum_{i=2}^{n} \lambda_{i1} \bar{V}^i_{C_1} + \gamma N_1 = 0, \tag{47}$$

$$\frac{\partial \mathscr{L}}{\partial E} = 0, \tag{48}$$

From equation (46) and (47), we obtain

$$T^{'}(Y_1, E) = -\frac{\sum_{i=2}^{n} \lambda_{i1} \bar{V}^i_{C_1} / \gamma N_1}{1 + \sum_{i=2}^{n} \lambda_{i1} \bar{V}^i_{C_1} / \gamma N_1} \frac{\partial B(Y_1, E)}{\partial Y_1} > 0. \tag{49}$$

From equation (48), we obtain

$$-\sum_{j=1}^{n-1} \lambda_{nj} \frac{\partial \bar{V}^n(C_j, Y_j, E)}{\partial E} - \sum_{j=1}^{n-2} \lambda_{(n-1)j} \frac{\partial \bar{V}^{n-1}(C_j, Y_j, E)}{\partial E} ... - \lambda_{21} \frac{\partial \bar{V}^2(C_1, Y_1, E)}{\partial E} = \gamma. \tag{50}$$

which could be rewritten as

$$-\sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \lambda_{ij} \frac{\partial \bar{V}^i(C_j, Y_j, E)}{\partial E} = \gamma \tag{51}$$

Substitute equation (44) into (51), we obtain

$$\sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \lambda_{ij} \bar{V}^i_{C_j} \frac{\partial B(Y_j, E)}{\partial E} = \gamma \tag{52}$$

Substitute equation (52) into (49), we obtain

$$T^{'}(Y_1, E) = -\frac{\sum_{i=2}^{n} \lambda_{i1} \bar{V}^i_{C_1} / \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \lambda_{ij} \bar{V}^i_{C_j} \frac{\partial B(Y_j, E)}{\partial E} N_1}{1 + \sum_{i=2}^{n} \lambda_{i1} \bar{V}^i_{C_1} / \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \lambda_{ij} \bar{V}^i_{C_j} \frac{\partial B(Y_j, E)}{\partial E} N_1} \frac{\partial B(Y_1, E)}{\partial Y_1} > 0. \tag{53}$$

Following the same procedure of calculation of Proposition 2, we obtain for type $j = 1, ..., n-1$,

$$T^{'}(Y_j, E) = -\frac{\sum_{i=j+1}^{n} \lambda_{ij} \bar{V}^i_{C_j} / \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \lambda_{ij} \bar{V}^i_{C_j} \frac{\partial B(Y_j, E)}{\partial E} N_j}{1 + \sum_{i=j+1}^{n} \lambda_{ij} \bar{V}^i_{C_j} / \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \lambda_{ij} \bar{V}^i_{C_j} \frac{\partial B(Y_j, E)}{\partial E} N_j} \frac{\partial B(Y_j, E)}{\partial Y_j} > 0 \tag{54}$$

Since there is no other types mimicking type n, we obtain

$$T^{'}(Y_n) = 0 \tag{55}$$

Proof of Corollary 3:

The social first-order condition of Lagrangean function (45) for C_j can be written as

$$\beta_j N_j V^j_{C_j} - \gamma N_1 = \sum_{i=j+1}^{n} \lambda_{i,j} \bar{V}^i_{C_j}. \tag{56}$$

Substitute equation (52) and (56) into policy rule in Proposition 3, i.e., equation (22),

$$T^{'}(Y_j) = -\frac{(\beta_j N_j V^j_{C_j} - \gamma N_j)/\gamma N_j}{1 + (\beta_j N_j V^j_{C_j} - \gamma N_j)/\gamma N_j} \frac{\partial B_j}{\partial Y_j}. \tag{57}$$

Rearrangement gives

$$T^{'}(Y_j) = -\frac{\beta_j N_j V^j_{C_j}/\gamma N_j - 1}{\beta_j N_j V^j_{C_j}/\gamma N_j} \frac{\partial B_j}{\partial Y_j}. \tag{58}$$

This can also be written as

$$T^{'}(Y_j) = \left(\frac{1}{\beta_j V^j_{C_j}/\gamma} - 1\right) \frac{\partial B_j}{\partial Y_j}. \tag{59}$$

Define $\Delta_j = \beta j V^j_{C_j}/\gamma \geq 1$, where $\gamma = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} \lambda_{ij} \bar{V}^i_{C_j} \frac{\partial B(Y_j, E)}{\partial E}$. We have

$$T^{'}(Y_j) = \frac{1 - \Delta_j}{\Delta_j} \frac{\partial B(Y_j, E)}{\partial Y_j}. \tag{60}$$