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Teun Draaisma,

Kathryn Gordon

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VALUING THE RIGHT TO TAX INCOMES: AN OPTIONS PRICING APPROACH

by Teun Draaisma and Kathryn Gordon

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VALUING THE RIGHT TO TAX INCOMES: AN OPTIONS PRICING APPROACH

This paper uses options pricing techniques to estimate the value of the government's tax claim on household or business incomes. It treats the annual tax claim as a European call option on taxable income (a European call is an option that can be exercised at its expiration date and not before). The option's expiration date is the end of the fiscal year and its strike price is the threshold level of income below which income is not subject to tax. The paper derives three alternative valuation formulas, each associated with an alternative functional form for the tax code (a flat tax, a step-function and a more general tax function). The application of options pricing theory to tax claims is found to be relatively straightforward. The approach proposed here could be used to refine accounting on the assets side of the government's balance sheet. It would not be more difficult to implement than many common applications of options theory.

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EVALUATION DU DROIT D'IMPOSITION DES REVENUS : APPROCHE BASEE SUR LE PRIX DES OPTIONS

Dans cette note, les techniques de détermination du prix des options sont utilisées pour estimer le montant de la créance fiscale de l'Etat sur les revenus des ménages et des entreprises. Cette créance fiscale annuelle est traitée comme une option d'achat à l'Européenne sur le revenu imposable. (Une option d'achat à l'Européenne est une option qu'on ne peut exercer qu'à la date d'expiration seulement et non avant.) La date d'expiration de l'option est la fin de l'exercice budgétaire et son prix d'exercice est le seuil en-dessous duquel le revenu n'est pas imposable. La note décrit trois formules possibles d'évaluation, dont chacune est associée à des modalités d'imposition différentes du point de vue du Code des impôts (un impôt à taux uniforme, un impôt progressif et une fonction fiscale plus générale). L'application de la théorie de la détermination du prix des options aux créances fiscales apparaît relativement simple. La méthode proposée dans cette note pourrait être utilisée afin de raffiner la comptabilité des actifs du bilan du gouvernement. Sa mise en oeuvre ne serait pas plus difficile que pour un bon nombre des applications courantes sur la théorie des options.

VALUING THE RIGHT TO TAX INCOMES: AN OPTIONS PRICING APPROACH

Teun Draaisma and Kathryn Gordon[1]

Governments acquire most of their revenues from tax receipts. Indeed the right to tax is one of the principal economic assets on a government's balance sheet. This right has an economic value that can be assessed using standard valuation techniques. The value of the right depends in part on variables that are controlled directly by the government: the type of tax (value added tax, income tax, excise tax etc.); the setting of various tax parameters; the type of sanctions imposed in the event of non-compliance with the tax code and the monitoring and enforcement techniques used to promote compliance. These policy settings influence how particular state variables -- taxable incomes for the income tax or sales of particular products for excise taxes -- translate into effective tax obligations. But the state variables are also influenced by factors that are outside the direct control of governments. These include, most importantly, random events (related to, for example, the business cycle, sectoral shocks or natural disasters) and the behavioural responses of taxable entities to the incentives embedded in the tax system.

The present paper explores the valuation of the government's right to impose a particular kind of contingent tax: the income tax. This tax is quite important in generating revenues for most governments; in recent years it has accounted for more than one-third of OECD governments' receipts (OECD, 1995) .

The paper treats the government's tax claim on incomes as a European call option (one that can only be exercised at a given point in time, the expiration date). The underlying security from which the value of the call is derived is the yearly income of the entity being taxed. For a tax option, the expiration date is the end of the fiscal year. At this time, the state variables (essentially taxable incomes) have assumed their final values and the government's claim on a given entity's income is either "in the money" (worth some positive amount) or "out of the money" (worth nothing). The "strike

1 Research Associate and Principal Economist, respectively, at the Organisation for Economic Co-operation and Development, 2 rue André Pascal, 75016 Paris, France.

price", K_0 , is the minimum or threshold level at which income becomes taxable. Since the government receives only some portion of the part of the income exceeding K_0 , additional parameters (reflecting how the tax system translates earned incomes into tax obligations) appear in the option pricing formula (relative to the pricing formula used to value financial securities).

An Options Valuation Formula for Tax Claims

Several alternative approaches to options pricing are available. The Black-Scholes (1973) derivation of the options pricing formula invokes arbitrage conditions based on the possibility of forming riskless hedges through continuous trading in the underlying security's market, the bond market and the options market . The present paper adopts an alternative approach deemed to be more suitable to the valuation of tax options.

The tax option problem differs from some other options valuation problems in that the securities markets needed to arbitrage between the underlying security (an enitity's taxable income) and the tax option do not exist. Thus, a pricing equilibrium related to riskless arbitrage between various security markets cannot be reasonably posited. The approach used in the present paper involves discounting in discrete time of the expected value of the cash pay-offs from the option. This approach was first advanced by Rubinstein (1976). He shows that, under fairly general conditions, this derivation yields results that are equivalent to those of Black and Scholes.

The application of this valuation technique to the government's income tax claims is reasonably straightforward. It consists of the following steps: i) define the payoffs from the option in different states of nature at the end of the fiscal year (that is, at the option's expiration date); ii) take the expected value of the payoff function under the assumption that taxable income is lognormally distributed; iii) discount this expected value at the risk free rate under the assumption that the government is risk neutral[2]. This paper presents three alternative solutions to this valuation problem,

[2] This assumption may be relaxed. See Rubinstein (1976) for a discussion of how market risk premia can be incorporated into the approach.

each corresponding to a different specification of the functional relationship between taxes and taxable income: 1) the flat or proportional tax; 2) taxes are a step function; 3) taxes are a smooth, progressive function of taxable income. These derivations use the following variables:

Q_t	the realised value of the tax claim at the end of the fiscal year,
Q	the current value of the tax claim on the income,
S_t	the realised value of taxable income at the end of the fiscal year,
S	value of taxable income at the end of the previous fiscal year,
K_0	threshold value of taxable income below which income is not taxed,
$\tau(S_t)$	the tax rate as a function of the taxable income,
r_F	one plus the (risk-free) interest rate,
$f(r)$	probability density function of random variable r (see definition below),
$N(\cdot)$	the standard normal cumulative density function,
μ_r	the mean of random variable r,
σ_r	the standard deviation of random variable r,

and two transformations:

$R_t = S_t / S,$

$r_t = ln\, R_t.$

Using this terminology, we begin by defining the payoff function. This gives the value of the tax obligation at the end of the fiscal year and is contingent on whether taxable incomes is "out of the money" (less than K_0) or "in the money" (greater than K_0):

(1) $$Q_t = \begin{cases} 0 & if\ S_t < K_0, \\ \tau(S_t)(S_t - K_0) & if\ S_t \geq K_0. \end{cases}$$

The expected value of Q_t is:

(2) $$\mathrm{E}(Q_t) = \mathrm{P}[S_t \geq K_0]\,\mathrm{E}[\tau(S_t)(S_t - K_0)|S_t \geq K_0] + \mathrm{P}[S_t < K_0]\,\mathrm{E}[0|S_t < K_0].$$

Using the transformation $R_t = S_t / S$, this is:

(3) $$\mathrm{E}(Q_t) = S\,\mathrm{P}\left[R_t \geq \frac{K_0}{S}\right]\mathrm{E}\left[\tau(S_t)\left(R_t - \frac{K_0}{S}\right)\middle|R_t \geq \frac{K_0}{S}\right].$$

Furthermore, substituting $r_t = ln\ R_t$, [3]:

(4) $$\mathrm{E}(Q_t) = S\,\mathrm{P}\left[r_t \geq \ln\left(\frac{K_0}{S}\right)\right]\mathrm{E}\left[\tau(S_t)\left(e^{r_t} - \frac{K_0}{S}\right)\middle|r_t \geq \ln\left(\frac{K_0}{S}\right)\right].$$

We thus establish the general formula for the expected value of tax revenues at the end of the fiscal year:

(5) $$\mathrm{E}(Q_t) = S\int_{\ln\frac{K_0}{S}}^{\infty} \tau\,(S_t)(e^r - \frac{K_0}{S})\,f(r)dr.$$

[3] Reminder: if R_t is lognormally distributed and $r_t = ln\ R_t$, then r_t is normally distributed and $ln\ \mu_R = \mu_r + \sigma_r^2 / 2$.

The three specific cases considered below -- the flat tax, the step-wise tax function, and the progressive, continuous tax function -- allow us to give specific functional forms to this integral and to solve it.

Case 1: Flat taxes (taxes are proportional to income)

The simple, proportional tax (or flat tax) is the most straightforward extension of the option pricing model to tax claims. Under the flat tax assumption, the pay-off function becomes:

(6) $$Q_t = \begin{cases} 0 & if\ S_t < K_0, \\ \tau\left(S_t - K_0\right) & if\ S_t \geq K_0. \end{cases}$$

The expected value integral in the case where $\tau(S_t) = \tau$ becomes:

(7) $$\mathrm{E}(Q_t) = \tau\ S \int_{\ln\frac{K_0}{S}}^{\infty} (e^r - \frac{K_0}{S}) f(r) dr.$$

This is the integral shown in Rubinstein's discrete time derivation except that the integral is multiplied by the tax parameter . Under the assumption that S_t is lognormal, this integral has the following solution (where $N(\cdot)$ is the standard normal cumulative distribution function):

(8) $$\begin{aligned} \mathrm{E}(Q_t) &= \tau \left(S\, e^{\mu_r + \frac{1}{2}\sigma_r^2} N(z + \sigma_r) - K_0 N(z) \right) \\ &= \tau \left(S\, \mu_R\, N(z + \sigma_r) - K_0 N(z) \right). \end{aligned}$$

with

$$z = \frac{\ln S - \ln K_0 + \mu_r}{\sigma_r}.$$

Using the risk neutrality assumption, we discount all tax revenues at the same discount rate (although clearly the riskiness associated with the tax obligations of different taxable entities are quite different). Discounting yields the final valuation result:

(9)
$$Q = \tau\left(SN(z+\sigma_r) - r_F^{-1} K_0 N(z)\right)$$
$$with \quad z = \frac{\ln S - \ln K_0 + \ln r_F}{\sigma_r} - \frac{\sigma_r}{2}.$$

This valuation formula exhibits many of the familiar features of more general options pricing models. For example, because of the asymmetry of the government's position with respect to shocks causing incomes to be unexpectedly high (as opposed to unexpectedly low), the tax option's value is positive in the volatility of taxable income. Likewise (as is intuitively appealing) the tax option's value is negative in its "strike price" (the threshold value at which income becomes taxable). The first term shows the expected value of the receipt (which reflects the expected value of the option being "in the money"). The second (negative) term reflects the value of the fact that income is not taxable below the threshold level.

Case 2: Tax rates are a step function

The statutory form of many income tax codes consists of a progressive "step" function (that is, tax rates climb by steps until reaching a top maximum rate which is applied to all incomes over a certain amount). Case 2 embodies this step function by adding two sets of parameters. First, the income levels at which the step function breaks are defined as $K_0, K_1, .., K_{n-1}$. Second the tax rates associated with each step in the tax function are defined as τ_1 ...., τ_n . Using these terms, we can define the payoffs from the tax option at the expiration date as follows:

$$\text{(10)} \qquad Q_t = \begin{cases} 0 & if \quad S_t < K_0, \\ \tau_i\left(S_t - K_0\right) & if \quad K_{i-1} \le S_t < K_i \quad for\ i = 1,2,..,n-1, \\ \tau_n\left(S_t - K_0\right) & if \quad K_{n-1} \le S_t < \infty, \end{cases}$$

Although it is rendered somewhat more complicated by the greater complexity of the tax code under consideration here, the broad outline of the derivation is identical. Incorporating the tax schedule's step function into this general formula yields:

$$\text{(11)} \qquad \mathrm{E}(Q_t) = S\left\{\sum_{i=1}^{n-1}\int_{\ln\frac{K_{i-1}}{S}}^{\ln\frac{K_i}{S}} \tau_i(e^r - \frac{K_0}{S})f(r)dr + \int_{\ln\frac{K_{n-1}}{S}}^{\infty} \tau_n(e^r - \frac{K_0}{S})f(r)dr\right\}.$$

After some straightforward manipulation of the integrals (see Annex), this yields the following results:

$$\text{(12)} \qquad \begin{aligned} \mathrm{E}(Q_t) = Se^{\left(\mu_r + \frac{1}{2}\sigma_r^2\right)}&\left\{t_n N(z_{n-1} + \sigma_r) + \sum_{i=1}^{n-1} t_i\left(N(z_{i-1} + \sigma_r) - N(z_i + \sigma_r)\right)\right\} \\ &- K_0\left\{t_n N(z_{n-1}) + \sum_{i=1}^{n-1} t_i\left(N(z_{i-1}) - N(z_i)\right)\right\} \\ with \quad z_i = \frac{\ln S - \ln K_i + \mu_r}{\sigma_r} \quad &for\ i = 0,1,..,n-1. \end{aligned}$$

Again, we assume that governments and markets are risk neutral, so that all tax revenue streams can be discounted at the same, risk free cost of capital. By rearranging terms we obtain:

$$Q = S\sum_{i=1}^{n}\left(\tau_i - \tau_{i-1}\right)N(z_{i-1} + \sigma_r) - r_F^{-1}K_0\sum_{i=1}^{n}\left(\tau_i - \tau_{i-1}\right)N(z_{i-1})$$

(13)

$$with \quad \tau_0 = 0 \quad and \quad z_i = \frac{\ln S - \ln K_i + \ln r_F}{\sigma_r} - \frac{\sigma_r}{2} \quad for\ i = 0,1,..,n-1.$$

Although obviously more complex, the interpretation of this valuation formula is analogous to that of the valuation formula for the flat tax rate. The first term is the expected value of the revenue stream given that the option is "in the money". The second term is the expected value (negative for the government but positive for tax payers) of the fact that income is not taxed below the threshold. What has changed (relative to the flat tax case) are the probability and tax weights appearing in the two terms. In each case, the weights are the tax rates for each step in the tax function multiplied by the corresponding probability weights.

Case 3: A more general income tax function

In practice, the relationship between the statutory structure of the tax code and the actual volume of tax revenue generated by its implementation is complex. The complexity stems from several sources. First, in an *ex ante* sense, agents will respond to the incentives embedded in the tax code when making decisions that influence their taxable incomes (for example, about levels of effort, about amounts and types of investment). Second, in an *ex post* sense, they will engage in other types of tax avoidance, both legal and illegal. Behavioural responses to the tax code reflect such factors as the perceived costs and benefits of tax compliance, the effectiveness of enforcement and the size of the deterrence threat (Slemrod, 1994). The present section proposes one (of many possible) general tax functions, the parameters of which could be calibrated to reflect the realities of tax implementation. The proposed function -- $\tau(S_t)=\bar{\tau}-\theta\ /S_t$ with $\bar{\tau} \in (0,1)$ and $0 \le \theta < \bar{\tau}K_0$ -- is continuous and strictly increasing in S_t for values above K_0, generates the following payoffs:

(15) $$Q_t = \begin{cases} 0 & if\ S_t < K_0, \\ \left(\bar{\tau} - \dfrac{\theta}{S_t}\right) S_t & if\ S_t \geq K_0. \end{cases}$$

with $\bar{\tau} \in (0,1)$ and $0 \leq \theta < \bar{\tau} K_0$.

Taking the expected value of these payoffs, we obtain:

(16) $$\mathrm{E}(Q_t) = S \int_{\ln \frac{K_0}{S}}^{\infty} \left(\bar{\tau} - \frac{\theta}{Se^r}\right)\left(e^r - \frac{K_0}{S}\right) f(r) dr.$$

Using a similar mathematical procedure to that used previously [see Annex], this can be shown to be equal to the following:

(17) $$\begin{aligned} \mathrm{E}(Q_t) &= \bar{\tau}\, S e^{\left(\mu_r + \frac{1}{2}\sigma_r^2\right)} N(z + \sigma_r) - \left(\bar{\tau} K_0 + \theta\right) N(z) + \theta \frac{K_0}{S} e^{\left(-\mu_r + \frac{1}{2}\sigma_r^2\right)} N(z - \sigma_r) \\ &= \bar{\tau}\, S \mu_R N(z + \sigma_r) \\ &\quad - \left(\bar{\tau} K_0 + \theta\right) N(z) \\ &\quad + \theta \frac{K_0}{S} \frac{e^{\sigma_r^2}}{\mu_R} N(z - \sigma_r), \\ with \quad z &= \frac{\ln S - \ln K_0 + \mu_r}{\sigma_r}. \end{aligned}$$

Assuming that governments and markets are risk neutral, we obtain the current value of the claim:

(18) $$\begin{aligned} Q &= \bar{\tau} S N(z + \sigma_r) - r_F^{-1}\left(\bar{\tau} K_0 + \theta\right) N(z) + r_F^{-2} \theta \frac{K_0}{S} e^{\sigma_r^2} N(z - \sigma_r), \\ with \quad z &= \frac{\ln S - \ln K_0 + \ln r_F}{\sigma_r} - \frac{\sigma_r}{2}. \end{aligned}$$

This can also be written as:

$$
(19) \quad \begin{aligned} Q &= \overline{\tau}\left(SN(z+\sigma_r) - r_F^{-1}K_0 N(z)\right) - r_F^{-1}\theta\left(N(z) - \frac{r_F^{-1}K_0}{S}e^{\sigma_r^2}N(z-\sigma_r)\right), \\ &with \quad z = \frac{\ln S - \ln K_0 + \ln r_F}{\sigma_r} - \frac{\sigma_r}{2}. \end{aligned}
$$

The terms inside the first parentheses give the expected value of the tax receipt and the adjustment to this value that is needed because incomes below the threshold value K_0 are not taxed. Unlike for Case 1 (where these same terms appear, but are evaluated at the flat tax rate), these are evaluated at the maximum marginal tax rate. The terms in the second parentheses correct for the fact that the first two terms are evaluated at the top marginal tax rate. These give the sizes of the adjustments to the terms in the first parentheses that are needed to account for the fact that not all incomes are taxed at the maximum rate. Note that if $\theta=0$, then the above formula reduces to the flat tax formula.

Conclusions

We have shown that, under certain assumptions, standard options pricing techniques can be applied to the valuation of a government's tax claims on incomes. Valuation techniques of this kind could have a number of applications in the area of public finance. First, they could provide inputs to the formulation of more rigorous public financial accounts. At the present time, no government (with the exception of New Zealand) keeps systematic balance sheet accounts. The approach suggested here could be used to refine accounting on the assets side of government balance sheet and would not be more difficult to implement than many common applications of options theory. Second, the recognition of a tax claim's relationship to a European call provides an analytical framework for improved understanding of the role the tax system plays in stabilizing incomes or, more precisely, in shifting portions of certain types of private risk onto the government. This is an issue that has exercised macroeconomists since the early discussions of automatic stabilizers that accompanied the Keynesian revolution. The current approach provides a more rigorous microeconomic foundation for understanding the role that governments' tax policies play in altering the financial risk of various taxable entities.

Annex

Three properties are used to solve the various integrals that appear in the expression for E(Q_t). The first two have been proven by Rubinstein (1976). This annex proves the third property.

Property 1:

$$\int_a^{\infty} f(x)dx = N\left(\frac{-a+\mu_x}{\sigma_x}\right);$$

Property 2:

$$\int_a^{\infty} e^x f(x)dx = e^{\left(\mu_x+\frac{\sigma_x^2}{2}\right)} N\left(\frac{-a+\mu_x}{\sigma_x}+\sigma_x\right);$$

Property 3:

$$\int_a^{\infty} e^{-x} f(x)dx = e^{\left(-\mu_x+\frac{\sigma_x^2}{2}\right)} N\left(\frac{-a+\mu_x}{\sigma_x}-\sigma_x\right).$$

Proof of property 3:

(20) $$e^{-x} f(x) = \frac{1}{\sigma_x\sqrt{2\pi}} e^{\left(\frac{-1}{2\sigma_x^2}(x-\mu_x)^2-x\right)}.$$

Working out the exponent leads us to:

(21) $$\frac{-1}{2\sigma_x^2}(x-\mu_x)^2 - x = -\mu_x + \frac{\sigma_x^2}{2} - \frac{\left(x-\left(\mu-\sigma_x^2\right)\right)^2}{2\sigma_x^2}.$$

Hence we can write

$$e^{-x} f(x) = e^{\left(-\mu_x+\frac{\sigma_x^2}{2}\right)} \frac{1}{\sigma_x\sqrt{2\pi}} e^{\left(\frac{-1}{2\sigma_x^2}\left(x-\left(\mu_x-\sigma_x^2\right)\right)^2\right)}$$, and consequently

$$\int_a^{\infty} e^{-x} f(x)dx = e^{\left(-\mu_x+\frac{\sigma_x^2}{2}\right)} \int_a^{\infty} \frac{1}{\sigma_x\sqrt{2\pi}} e^{\left(\frac{-1}{2\sigma_x^2}\left(x-\left(\mu_x-\sigma_x^2\right)\right)^2\right)} dx$$

(22) $$= e^{\left(-\mu_x+\frac{\sigma_x^2}{2}\right)} \int_{\frac{a-\left(\mu_x-\sigma_x^2\right)}{\sigma_x}}^{\infty} f(z)dz = e^{\left(-\mu_x+\frac{\sigma_x^2}{2}\right)} \int_{-\infty}^{\frac{-a+\mu_x}{\sigma_x}-\sigma_x} f(z)dz$$

$$= e^{\left(-\mu_x+\frac{\sigma_x^2}{2}\right)} N\left(\frac{-a+\mu_x}{\sigma_x}-\sigma_x\right).$$

.

Finally, in case 2, where the tax function is stepwise, we simply write $\int_a^b g(x)dx$ as the difference of two integrals to which we know the solution: $\int_a^\infty g(x)dx - \int_b^\infty g(x)dx$.

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