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Luis Oscar Herrera Rodrigo Valdés

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Huérfanos 1175, primer piso.
Teléfono: (56-2) 6702475   Fax: (56-2) 6702231

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THE EFFECT OF CAPITAL CONTROLS ON INTEREST RATE DIFFERENTIALS

Luis Oscar Herrera
Gerente de Programación Macroeconómica
Banco Central de Chile

Rodrigo Valdés
Economista Senior
Gerencia de Investigación Económica
Banco Central de Chile

Resumen

Este trabajo presenta un modelo de arbitraje de tasas de interés internacional bajo un esquema de costo de entrada y de salida desde el mercado local. Se busca medir el máximo efecto potencial de controles de capital como el encaje no remunerado sobre el diferencial de tasas. Usando un modelo de optimización dinámica con incertidumbre y costos de transacción, se cuantifica el efecto de estos impuestos. Utilizando una regla optima (S,s) se determinan los límites que gatillan la entrada o salida masiva de capitales. También se calculan los diferenciales de tasas máximos sustentables para varios plazos de madurez y se estudia la sensibilidad de los resultados a cambios en los parámetros. Para el caso chileno, usando parámetros estimados, el modelo muestra que los efectos de utilizar controles de capitales sobre el diferencia de tasas son menores a los que sugiere un análisis estático.

Abstract

In this paper we present a model of international interest rate arbitrage under conditions of entry and exit costs to and from the domestic capital market. We seek to measure the maximum potential effect of capital controls, such as non-interest paying reserve requirements, on interest rate differentials. We quantify the effect of such taxes using a dynamic optimization model with uncertainty and transaction costs. An optimal (S,s) rule gives the limits for interest rate differentials that trigger massive capital inflows and outflows. We also calculate maximum sustainable interest rate differentials for various maturities and study the effect of parameter changes. Using parameters estimated for the Chilean economy, the model shows that the effect of capital controls on interest rate differentials is considerably smaller than what static calculations suggest.

We thank José de Gregorio, Leonardo Hernández and participants of a Central Bank of Chile seminar for helpful comments. All remaining errors are our responsibility. The points of view expressed in this paper are those of the authors, and do not necessarily coincide with opinions or policies of the Central Bank of Chile. E-mail address: rvaldesx@condor.bcentral.cl

1 Introduction

The main reasons for imposing capital inflow controls are to curb massive capital inflows, avoid real exchange rate (RER) appreciation, bias the structure of external liabilities towards long-run securities, and generate room for maneuver for monetary policy (in the presence of RER targets). All these goals can be summarized as having larger international interest rate differentials, especially at short-run maturities, without generating capital inflows. The policy design often takes the form of an inflow tax, or some kind of entry fee, and it is usually introduced in periods of abundant international liquidity. In a very different environment, capital controls also are used as a defense against capital flight, in which case the policy design usually takes the form of an exit tax.

Several types of capital controls used by many countries during the last 10 years can be thought of as entry and exit transaction costs. For example, policy instruments such as proportional entry and exit taxes, reserve requirements paying below-market interest rates, and transaction fees, all involve an irreversible payment.[1] The cross-country experience is abundant.[2] Unremunerated reserve requirements (URR) have been used by Chile since 1991, Colombia since 1993 and Malaysia since 1994, as well as by Spain in 1989 and Thailand in 1994–95. Direct entry taxes were imposed in Brazil in 1993–94 and Malaysia in 1994. During the 70's and 80's, capital outflows had to cope with dual exchange rates regimes.

The aim of this paper is to assess quantitatively the effect of this type of capital controls on international interest rate differentials using the case of Chile during the 90's, emphasizing the role of risk and the irreversibility of inflow and outflow costs.[3] More specifically, we seek to measure the maximum potential effect of these

[1]Other types of capital controls include minimum investment periods, quantitative restrictions on the sale of short-term liabilities to foreigners, and bans on investing in foreign securities.

[2]See, e.g., Cárdenas and Barrera (1997), Cardoso and Goldfajn (1997), De Gregorio (1995), Valdés-Prieto and Soto (1996) and World Bank (1997).

[3]In this paper we refer to interest differentials as the difference between domestic and international yields measured in the same currency. The simplest interpretation is to assume a fixed exchange rate. Another is to focus on the difference between on-shore and off-shore rates.

controls on interest differentials explicitly considering that investors' entry and exit decisions —and hence their investment horizon— are contingent on the state of the economy and part of a dynamic optimization process that takes into account entry and exit costs as well as the stochastic process followed by interest rate differentials. In that set-up, an optimal (S,s) rule (as in Dixit, 1989) gives sustainable limits for interest differentials —limits that define a band within which no massive capital inflows or outflows occur. The paper shows that the stochastic process followed by the differential, as well as the size of entry and exit costs, is important in determining these limits.

Besides being a matter of theoretical interest, this assessment is a key issue from a policy perspective. If policy makers overestimate the effect of controls, the policy mix can produce results that work completely against the initial purpose of the controls. For instance, if the authority imposes controls in pursuit of monetary autonomy with exchange rate targets and their effect is smaller than predicted, they can end up generating a massive appreciation. This can also (wrongly) lead to a negative evaluation of the effectiveness of the controls, when the real culprit is the level of domestic interest rates.

The most important conclusion of this paper is that the impact of controls is considerably smaller than what static (and commonly used) calculations suggest. For example, according to the model, and using parameters estimated for the Chilean economy, the maximum interest-rate differential for 3-month operations generated by a 1-year 30% URR is approximately 2.3% per year, while calculations that fix the investment horizon estimate a differential equal to 10.5%. For 12-month operations the estimated differentials are 2.53% and 1.25%, respectively. The paper also shows that higher variability and a lower degree of interest rate mean reversion, and higher entry and exit costs, generate higher differentials for short-term maturity yields.

The paper is organized as follows. In section 2 we present the basic model of arbitrage and interest rate differentials under capital controls, which is the basis for deriving maximum and minimum instantaneous interest differentials and the bounds of the yield curve. In section 3 we generalize the basic model by relaxing two simplifying assumptions, and work through some numerical examples. In section 4 we apply the model to the Chilean URR case, calculating its effect under four different estimates of the stochastic interest rate differential process. We also compare the results to the static solution that fixes the investment horizon ex-ante. Finally, in section 5 we make some concluding remarks.

2 A Simple Model of Arbitrage and Interest Rate Differentials

In this section we develop a simple model of arbitrage and international interest rate differentials taking into account a fixed entry cost to the recipient country and assuming that the domestic interest rate follows a given stochastic process. We further assume that the entry cost is fully credible and there is no evasion. As mentioned above, many types of control on capital inflow can be thought of as a fixed entry cost. The model explicitly considers the fact that the time horizon of foreign investment is endogenous to the state of the economy and that entry and exit decisions are part of a dynamic optimization problem. Given a fixed entry cost and the parameters governing the stochastic process of interest rates, the model allows us to determine the maximum (minimum) instantaneous interest rate differential that does not trigger massive capital inflows (outflows). All this analysis is carried out under the assumption of a fixed and fully credible exchange rate regime.[4]

In order to keep the analysis in this section as simple as possible, we make two assumptions. First, we assume that whereas the international interest rate is fixed, the recipient country's interest rate follows a Brownian motion without drift. And second, we assume that all the proceeds generated in the recipient country are reinvested abroad —or equivalently, that the fixed entry payment allows the investor to keep only the original investment in the recipient country. We will relax these two assumptions

[4]Bentolila and Bertola (1987) study the effects on a firm's labor demand of hiring and firing costs using a similar methodology.

in section 3.

Once we determine the maximum (minimum) sustainable instantaneous interest rate differential, we derive the maximum (minimum) differential for bonds of different maturities from a simple expectations hypothesis model. That is, we derive the maximum (minimum) sustainable yield curve considering international arbitrage opportunities and expected future rates.

2.1 Random Walk and No Re-Investment

We assume that time is continuous and denote the international interest rate by r^*. We also assume that international investors are risk-neutral and they evaluate whether to invest in a small recipient country that charges an entry cost k per dollar invested. For that purpose, investors compare the domestic return (domestic from the recipient country's point of view) to the international interest rate. Because of the fixed entry cost, it is not only relevant to consider the instantaneous return differential, but also the size of the entry fee. Moreover, given that this is an irreversible one-time payment, all expected future return differentials also matter. Letting ρ be the domestic interest rate, investors compare getting $\rho - r^*$ today, plus eventual future gains, with the fixed entry cost k.

Let us define the function $V(\rho, r^*)$ as the dollar value that investors assign to the possibility of investing in the domestic country, without considering the fixed entry cost k. This value can be thought of as the price of a license to invest in the recipient country and takes into account both instantaneous gains and the possibility of future gains. Of course, whenever $V(\rho, r^*)$ is larger than k there will be massive capital inflows, while whenever $V(\rho, r^*)$ is smaller than zero (or a negative constant if there are exit costs) there will be massive capital outflows. Thus, the sustainable interest rate differential will lie between two bounds. If it moved outside the bounds, massive capital flows would force the domestic rate back inside the band.

With a fixed international interest rate, the interest rate differential bounds have as their counterpart a maximum and a minimum domestic interest rate, denoted by

R and r, respectively.[5] Obviously, k will be a key determinant of (R, r). If $k = 0$, then necessarily $R = r = r^*$, because any difference would be arbitraged away.

Assuming the proceeds have to be invested outside the recipient country and that r^* is constant, the function $V(\rho, r^*)$ —$V(\rho)$ hereafter— has to satisfy the following no-arbitrage equation (while the domestic interest rate is inside the band (R, r) in which there are no incentives for capital flows):

$$r^* V(\rho) dt = (\rho - r^*) dt + E_t[dV(\rho)], \quad (1)$$

where d denotes instantaneous change, t is time and E_t represents expectations taking into account all the information available up to time t. This equation simply says that the expected return of investing in the recipient country has to be equal to its alternative cost. In other words, the sum of the instantaneous interest rate differential and the expected capital gains has to equal the opportunity cost of holding the license for investing in the domestic economy.[6]

In addition, we assume that while domestic interest rates are inside the no-arbitrage band, they follow a Brownian motion without drift:

$$d\rho = \sigma d\omega, \quad (2)$$

where $d\omega$ is a standard Wiener process.

Using Ito's Lemma in the last term of (1) we obtain:

$$E_t[dV(\rho)] = \frac{1}{2} V_{\rho\rho}(\rho) \sigma^2 dt, \quad (3)$$

where $V_{\rho\rho} = d^2V/d\rho^2$. Thus, we conclude that while the interest rate differential is within the bounds of no-arbitrage opportunities, $V(\rho)$ follows the following differential equation:

$$r^* V(\rho) = \rho - r^* + \frac{1}{2} V_{\rho\rho}(\rho) \sigma^2. \quad (4)$$

[5]Thus, $R - r^*$ and $r - r^*$ are the maximum and minimum interest rate differentials, respectively.

[6]A more basic way of describing $V(\rho)$ is using the Bellman equation of this problem. As it is known that future decisions will be optimal, we have $V(\rho) = (\rho - r^*)dt + e^{-r^* dt} E_t[V(\rho + d\rho)]$.

The solution to this equation is standard and is given by:

$$V(\rho) = \frac{\rho - r^*}{r^*} + C_1 e^{\frac{\rho\sqrt{2r^*}}{\sigma}} + C_2 e^{-\frac{\rho\sqrt{2r^*}}{\sigma}}, \tag{5}$$

where C_1 and C_2 are two constants to be determined by border conditions. On the one hand, since we have defined the bounds of (R, r) as the domestic interest rates at which capital massively moves into and out of the recipient country, it must be the case that:

$$V(R) = k \text{ and } V(r) = 0,$$

which provide the two border conditions to solve (5). On the other hand, in equilibrium, expected arbitrage gains cannot exist. This requires two smooth-pasting conditions given the fact that the domestic rates stochastic process changes at the borders of (R, r).[7] These conditions are:

$$V_\rho(R) = 0 \text{ and } V_\rho(r) = 0,$$

which in turn allow us to find R and r.

In sum, given the stochastic process of the local interest rate described by σ, along with a fixed international interest rate r^*, and an entry cost k, there is a maximum domestic interest rate R and a minimum rate r, such that no massive flows occur. These two rates, plus the two constants C_1 and C_2, solve the following non-linear system of equations:

$$\begin{aligned}
\tfrac{R-r^*}{r^*} + C_1 e^{\frac{R\sqrt{2r^*}}{\sigma}} + C_2 e^{-\frac{R\sqrt{2r^*}}{\sigma}} &= k \\
\tfrac{r-r^*}{r^*} + C_1 e^{\frac{r\sqrt{2r^*}}{\sigma}} + C_2 e^{-\frac{r\sqrt{2r^*}}{\sigma}} &= 0 \\
\tfrac{R\sqrt{2r^*}}{\sigma} C_1 e^{\frac{R\sqrt{2r^*}}{\sigma}} - \tfrac{R\sqrt{2r^*}}{\sigma} C_2 e^{-\frac{R\sqrt{2r^*}}{\sigma}} &= \tfrac{1}{r^*} \\
\tfrac{r\sqrt{2r^*}}{\sigma} C_1 e^{\frac{r\sqrt{2r^*}}{\sigma}} - \tfrac{r\sqrt{2r^*}}{\sigma} C_2 e^{-\frac{r\sqrt{2r^*}}{\sigma}} &= \tfrac{1}{r^*}
\end{aligned} \tag{6}$$

As there is no closed-form solution to this system, numerical methods must be used to find the final solution. In order to have a reference of the value of the maximum and

[7] At the borders, the domestic interest rate stochastic process becomes controlled by a reflecting barrier because capital inflows (outflows) stop any increase (decrease). In order to avoid arbitrage opportunities, $V(.)$ has to approach the borders smoothly. See Dixit (1993).

minimum differentials in this economy, as well as of the shape of the $V(\rho)$ function, we calibrate the system with a concrete example. We assume the following parameters: the world interest rate is 6% annual, the fixed cost k is \$0.0257 per dollar, and the standard deviation σ is 1% per year.[8] The solution yields $R = 7.49\%$ and $r = 4.73\%$. Thus, the maximum sustainable interest differential under these parameter values is 1.49%. Figure 1 shows the $V(\rho)$ function. It is an S-shaped line that smoothly approaches the extremes values of 0 and 0.0257. Notice that when the domestic and the international interest rate are equal —and so there are no instantaneous gains— the license value is strictly positive (approximately \$0.011). As expected, there are option values involved in the problem. Because of the existence of an option to exit in the future, there are no capital outflows when the domestic interest rate is (marginally) smaller than the international rate.

2.2 Yield Curve

So far, the model allows us to calculate sustainable instantaneous interest rate differentials. In this section we study yield differentials on bonds of different maturities. In particular, we derive the upper and lower bounds of the entire yield curve.

Let $P(\rho, t, T)$ denote the price of a zero-coupon bond in time t, with maturity in T, under a current local interest rate equal to ρ, taking into account that $r \leq \rho \leq R$ for all t. With risk-neutral agents the bond price has to satisfy the following equation:

$$\rho P(\rho, t, T) dt = E_t[dP(\rho, t, T)]. \tag{7}$$

The instantaneous interest rate has to be equal to the expected capital gain from holding the bond. Using Ito's Lemma in (7) yields the following partial differential equation for $P(\rho, t, T)$:

$$\rho P(\rho, t, T) = P_t(\rho, t, T) + \frac{1}{2} P_{\rho\rho}(\rho, t, T)\sigma^2, \tag{8}$$

[8] We report annual rates, but use continuous-time equivalents in all calculations. $k = 0.0257$ is the equivalent of a URR with holding period of one year, calculated as $URR \times (e^{r^*} - 1)/(1 - URR)$, where URR is the required rate. Section 3 gives more realistic representations.

The solution of this equation has to satisfy the following border conditions:

$$P(\rho, T, T) = 1, \forall \rho, \text{ and}$$
$$P_\rho(R, t, T) = P_\rho(r, t, T) = 0.$$

These conditions follow from the fact that the price of the bond in T is equal to 1, independently of the value of ρ in T, and that in equilibrium there cannot be discrete capital gains when ρ approaches the limits R and r and the stochastic process of ρ changes. We solve this equation using a discrete-time approximation and numerical methods (further details in section 3).

Given $P(\rho, t, T)$, the yield to maturity of a bond with residual time $T - t$ is given by the log-difference between the price at maturity (equal to 0) and the current price, divided by the residual time:

$$\Psi(\rho, T - t) = -\frac{\ln P(\rho, t, T)}{T - t}. \tag{9}$$

Finally, the maximum and minimum domestic interest rates for different maturities are given by $\Psi(R, T - t)$ and $\Psi(r, T - t)$.

The parameters of the numerical example mentioned before produce the following results. At maturities equal to 3, 6, and 12 months the maximum and minimum yields are given by 7.23%, 7.11% and 6.95%, and 4.99%, 5.10% and 5.27%, respectively.

3 A More General Set-Up

In this section we relax the two simplifying assumptions made in the previous section. We now assume that it is possible to re-invest the proceeds in the local economy and that domestic rates follow a mean reverting stochastic process. The cost of making these assumptions is that in this case the differential equation governing the $V(\rho)$ function becomes more complicated. The benefit is a more realistic estimation of sustainable differentials.

3.1 AR(1) Process and Re-investment

Let us assume now that domestic interest rates follow a Ornstein-Uhlenbeck stochastic process —the equivalent of an AR(1) process in continuous time. It is expected that the domestic rate will converge to the value $\bar{\rho}$ in the long run (eventually, equal to the international interest rate). The domestic rate evolves according to:

$$d\rho = w(\bar{\rho} - \rho)dt + \sigma d\omega, \tag{10}$$

where $d\omega$ is a standard Wiener process.

When re-investment is possible, the interest rate process described by (10) implies that the $V(\rho)$ function now satisfies the following differential equation:

$$(r^* - \rho)V(\rho) = \rho - r^* + w(\rho - \bar{\rho})V_\rho(\rho) + \frac{1}{2}V_{\rho\rho}(\rho)\sigma^2. \tag{11}$$

The border conditions are the same as before, and for simplicity we find the solution of $V(\rho)$, R, and r with a numerical procedure.

The partial differential equation for bond prices (8) also changes with the new interest rate process. In particular, $P(\rho, t, T)$ now satisfies:

$$\rho P(\rho, t, T) = P_t(\rho, t, T) + w(\bar{\rho} - \rho)P_\rho(\rho, t, T) + \frac{1}{2}P_{\rho\rho}(\rho, t, T)\sigma^2, \tag{12}$$

with the same border conditions as before. Finally, the yield curve continues to be described by (9).

3.2 Discrete-Time Approximation and Numerical Solution

In order to solve equation (11) numerically, we use a discrete-time approximation of (10).[9] Specifically, we take time intervals of fixed-size τ and innovations of ρ of fixed-size ε. These innovations follow a binomial process whose parameters are chosen such that the mean and variance of this process match the corresponding parameters of the continuous-time process. Therefore,

[9]See, for example, Dixit and Pindyck (1994), Ch. 3.

$$\Delta\rho = \begin{cases} +\varepsilon & \text{with probability } q(\rho) \\ -\varepsilon & \text{with probability } 1 - q(\rho), \end{cases}$$

where

$$q(\rho) = \frac{1}{2}\left[1 + \frac{w(\bar{\rho} - \rho)\tau}{\varepsilon}, \right]$$

and

$$\varepsilon = \sigma\sqrt{\tau}.$$

Given the binomial process parameters, we can write the Bellman equation associated with equation (11) in discrete-time as the following difference equation:

$$V(\rho) = (\rho - r^*)\tau + e^{-(r^* - \rho)\tau}\left[q(\rho)V(\rho + \varepsilon) + (1 - q(\rho))V(\rho - \varepsilon)\right], \qquad (13)$$

which equals k and 0 at the limits R and r, respectively.

In order to find the $V(\rho)$ function we use a recursive method. Starting from an arbitrary initial solution we iterate over the following two equations:[10]

$$\hat{V}_i(\rho) = (\rho - r^*)\tau + e^{-(r^* - \rho)\tau}\left[q(\rho)V_i(\rho + \varepsilon) + (1 - q(\rho))V_i(\rho - \varepsilon)\right]$$

$$V_{i+1}(\rho) = \min\langle \max\langle 0, \hat{V}_i(\rho)\rangle, k\rangle,$$

using also the condition $\hat{V}(r) = \hat{V}(r - \varepsilon)$ and $\hat{V}(R) = \hat{V}(R + \varepsilon)$ in order to satisfy the smooth-pasting conditions.

The bond price differential equation (12) also has a discrete-time representation. Given time intervals of size τ, the bond price has to satisfy:

$$P(\rho, t - \tau, T) = e^{-\rho\tau}\left[q(\rho)P(\min\langle \rho + \varepsilon, R\rangle, t, T) + (1 - q(\rho))P(\max\langle \rho - \varepsilon, r\rangle, t, T)\right], \qquad (14)$$

where R and r are the maximum and minimum instantaneous interest rates. The values of $P(\rho, t, T)$ can be calculated recursively starting from $P(\rho, T, T) = 1$.

[10] It can be shown that the operator $T : V_i = TV_{i-1}$ satisfies Blackwell sufficient conditions. Thus, the iterations over the operator T converge to the solution V (Stokey and Lucas, 1989, p. 54.).

3.3 Changes in Parameters

Using the model presented so far it is interesting to analyze the effects of several parameter changes. This section presents some exercises along these lines, which are useful both for evaluating the sensitivity of the results to parameter changes and for understanding the mechanics in place.

The baseline parameter values correspond to one of the estimations for the case of Chile that will be discussed below and are based on a simple AR(1) model of the real interest rate differential. In particular, we consider $\sigma = 0.04212$, $w = 0.3216$, $k = 0.0257$ and $\bar{\rho} = r^*$. The value of k is the dollar equivalent of a URR of 30% with a one-year holding period. These parameters imply a maximum and a minimum instantaneous differential equal to 3.64% and –3.51%, respectively.[11] The maximum differential for a 3-month rate is 2.31%.

In table 1, we present the effect of changing parameters on the instantaneous maximum and minimum differential ($R - r^*$ and $r - r^*$) and on sustainable maximum differentials for 3, 6 and 12-month bonds.

Interest Rate Volatility A higher variance in the interest rate process generates larger sustainable instantaneous differentials. The intuition underlying this is as follows. Consider a particular pair (R, r). When the domestic rate is near the upper bound R, a higher volatility produces lower future expected differentials because although the domestic rate cannot rise further (massive inflows make R a reflecting barrier), it can fall. Therefore, investors require a higher differential for entry, and R has to be higher. At the lower bound r the opposite happens: higher volatility produces higher expected differentials —outflows preclude the domestic rate from being lower than r. Hence, investors are willing to accept lower differentials before they decide to exit, so r has to be smaller. In terms of the option-values behind

[11] In all simulations we assume an international interest rate equal to 6%. Because this rate acts as the discount rate in the model, the estimated differential varies marginally with different assumptions about r^*. Obviously, the value of (R, r) varies almost one-to-one with the international interest rate. With $r^* = 5\%$, the maximum differential decreases to 3.33%, while R decreases from 9.64 to 8.33%.

this problem, we have the standard effect of volatility, namely that higher volatility increases the value of the options. By entering, investors are giving up the option to enter later on. Thus, higher volatility implies that they are giving up something more valuable and so ask for a higher interest rate differential. Of course, when entering investors get the exit option, which is more valuable with higher volatility. However, as this option will most likely be exercised in the future, the present value of its change in value is smaller that what investors are giving up. The opposite happens when investors assess whether to exit. In our numerical example, if one considers $\sigma = 0.030$ (instead of 0.042) the instantaneous maximum differential changes from 3.64% to 2.81% and the minimum from –3.51% to –2.92%.

A lower variance moves the maximum sustainable yield curve down for shorter maturities, while it can move it up in the case of longer maturities. This happens because higher volatility affects R and r in opposite directions. Thus, for a long enough horizon, even conditional on a higher initial short rate, the average of short (instantaneous) rates can be smaller. In the example, the maximum differential for 3-month bonds decreases from 2.31% to 2.06%, while for 1-year bonds it rises from 1.19% to 1.20%.

Interest Rate Mean Reversion A higher mean reversion coefficient means that the effects of domestic interest rate innovations have a shorter life. Conditional on interest rates being above the mean (or long-run rate), a higher reversion generates smaller interest rates. Thus, the maximum sustainable interest rate differential is larger with a higher mean reversion coefficient. The minimum sustainable differential is also larger (in absolute value). Exit occurs at lower rates when there is a higher degree of mean reversion because investors on average expect higher future interest rates. Numerically, if one considers a reversion coefficient $w = 0.05$ (meaning that shocks have a half-life of 13.8 years), instead of the baseline $w = 0.3216$ (equivalent to a half-life of 2.2 years), the maximum instantaneous differential decreases from 3.64% to 3.55%, while the minimum differential changes from –3.51% to –3.42%. The maximum yield curve moves downwards for all maturities, although more so for short horizons. The 3-month differential decreases from 2.31% to 2.26%.

Long Run Interest Rate Even if the domestic long-run rate is higher than the domestic rate ($\bar{\rho} > r^*$) it is possible to have both an instantaneous interest rate differential and differentials on bonds of different maturities. Of course, the higher the difference between the two interest rates, the smaller will be the maximum sustainable differential and the larger will be the minimum sustainable differential. Numerically, if one considers a long-run rate 150 basis points above the international rate, the maximum instantaneous differential decreases to 3.41%, while the minimum differential increases (in absolute value) to –3.68%. The maximum sustainable yield curve moves down for all maturities.

Entry Cost A higher entry cost generates a wider (R, r) band, allowing higher maximum and minimum interest rate differentials. The intuition for this is straightforward. Entry occurs at higher rates because investors need higher proceeds to pay a higher entry cost. Exit occurs at lower domestic interest rates because the option (to re-enter) that investors get has a lower value —the irreversibility is larger. Using a URR of 20% in the numerical example (instead of 30%) produces a maximum instantaneous differential of 3.04% and a minimum differential of –2.94%. The maximum yield curve shifts downwards in a relatively uniform way for all maturities. The maximum 3-month differential decreases by 47 basis points to 1.85%.

Exit Cost Finally, it is interesting to analyze the effect of exit costs, which are taxes paid at the moment the outflow occurs. The effect on the entry decision is analogous to an entry cost, although in the case of an exit cost what matters is its expected present value. This, in turn, depends critically on the investment horizon. The effect on the exit decision is direct: it is costly to abandon the recipient country, so exit occurs at larger (in absolute value) differentials.[12] With an exit cost equal

[12] Labán and Larraín (1996) show that lowering exit costs may increase capital inflows. In their model the irreversibility created by exit costs decreases and so does the option value of waiting. In our case, although we do not measure flows directly, there is a similar effect: a lower exit cost

to 0.01 per dollar (equivalent to almost 40% of the fixed entry cost) the numerical example shows that the maximum instantaneous differential increases from 3.64% to 4.06%, while the minimum differential increases (in absolute terms) from –3.51% to –3.89%. As in the case of entry costs, the whole maximum yield curve shifts upwards.

4 An Application: The URR in Chile

This section presents an estimation of the effect of the URR used in Chile based on the model described so far and includes a further generalization. The Chilean URR has a one-year withholding period and applies to all capital inflows since 1991.[13] In order to evaluate whether the dynamic optimization structure of the model matters for the results, we compare the estimations to those of a static model. In the static case, one assumes a fixed investment horizon to calculate the implied tax and differential.

4.1 Interest Rate Stochastic Process Estimation

A key step before applying the model is to estimate the parameters governing the stochastic interest rate differentials process. We use two alternative interest differential series. The first one is a covered differential calculated with data from the forward exchange rate market. Because this series is relatively short (and includes only one change in monetary policy) we also calculate a real interest rate differential.

We calculate the covered differential (CD) with weekly data (from January, 1994 to August, 1996) as follows:

$$CD = \frac{1 + PRBC}{(1 + \text{ Forward Premium}) \times (1 + Libor3)} - 1,$$

where $PRBC$ is the UF rate on 90-day Central Bank of Chile notes, Forward Premium is the average implicit devaluation rate in 90-day UF/dollar forward contracts, and

decreases the maximum sustainable differential.

[13]The only important exemption is Foreign Direct Investment, which does not pay any tax. Bank foreign exchange-denominated deposits have a URR withholding period equal to the deposit's maturity. Apart from giving up for one year 30 cents of each dollar inflow, investors have the option of paying a fixed cost (tax) upon entry equivalent to the opportunity cost of the URR.

$Libor3$ is the 3-month dollar Libor rate.[14] This differential has been quite stable since 1995 with an average annual rate of 3%.[15]

We calculate the real interest rate differential (RD) with monthly data (from January, 1991 to August, 1996) as:[16]

$$RD = \frac{(1 + PRBC) \times (1 + CPI^*)}{1 + Libor3} - 1,$$

where CPI^* is the annual US inflation rate.[17] The RD series has an average of 4% and includes 4 different domestic monetary policy regimes (2 expansions and 2 contractions).

We consider two alternative processes for interest differentials. First, we estimate a simple AR(1), from which we can directly use the model described in section 3. In this case we assume that the differential in time t, D_t, satisfies the following equation:

$$D_t = \bar{D} + \omega(D_{t-1} - \bar{D}) + \xi_t,$$

where $\bar{D}$ is the long-run differential (e.g. due to country risk) and ξ_t is an i.i.d. zero mean constant variance innovation. In this case we estimate:

$$D_t = \alpha + \omega D_{t-1} + \xi_t, \tag{15}$$

where $\alpha = (1 - \omega)\bar{D}$.

The second stochastic process we consider —and which allows further generalizations in the model— is an AR(1) with two long-run rate regimes that follow a Markov chain (Hamilton, 1990). This process tries to capture the idea of two states of monetary policy: a contractionary stance and a expansionary one. In both states we assume the same autoregressive parameter and the same variance of innovations.

[14] The UF is a unit of account that is indexed daily to inflation and used in nearly all financial transactions in Chile. For our purposes, UF acts as the Chilean currency.

[15] With no country-risk or capital controls (or other taxes), this differential should be zero.

[16] Although there is data available before 1991, capital account regulations and the structure of the Balance of Payments were completely different.

[17] Because of data availability, we do not consider real depreciation expectations. The officially announced (and probably credible) policy was a 2% real depreciation per year. Subtracting this 2% from RD does not change the results in any significant way.

The key difference is the long-run rate to which the economy converges. Moreover, this process allows for the possibility of sudden changes in states, but smooth changes in interest rates.[18] The model we use in this case to calculate the differential bounds is discussed below.

Formally, for an AR(1) with regime-switching we assume the following process for the differential D_t:

$$D_t = \bar{D}_i + \omega(D_{t-1} - \bar{D}_i) + \epsilon_t$$

where

$$\bar{D}_i = \begin{cases} \bar{D}_1 & \text{in state 1 (loose policy), and} \\ \bar{D}_2 & \text{in state 2 (tight policy),} \end{cases}$$

ϵ_t is an i.i.d. innovation, eventually with a normal $N(0, \sigma^2)$ distribution, and where the economy switches between states according the following transition matrix:

$$P = \begin{bmatrix} p_1 & 1 - p_1 \\ 1 - p_2 & p_2 \end{bmatrix},$$

in which P_{ij} denotes the probability of switching from state i to state j. As in the case of the simple AR(1), we estimate an equivalent to (15).

To estimate the simple AR(1) process we use OLS. Table 2 presents the results for the two interest differential series. Because the series have different frequencies, the parameters are not comparable.[19] The results are satisfactory, showing highly significant parameters.

We estimate the regime-switching process through maximum likelihood. Table 3 presents the results, which show that the log-likelihood increases compared to the simple AR(1) process and that there are two clearly different states for long-run interest rates. Moreover, the difference between the parameters α_1 and α_2 is significantly different from zero. Notice, however, that the two-regime model makes more sense under the real differential series, because the covered-interest differential data mainly relates to just one regime.[20]

[18] Typically, a change in monetary policy involves moderate and consecutive interest rate changes.

[19] Table 4 presents comparable parameters (annual equivalent).

[20] In fact, the probability of staying in state 2 is close to zero when one considers the annual

4.2 Static versus Dynamic Solution

The estimations presented in last section allow us to calculate the maximum interest differentials that the Chilean URR can sustain. For this we need to transform the estimated parameters into their annual equivalent. Table 4 presents these results as well as the expected time the economy remains in each regime.[21] The AR(1) Markov of the covered interest differential series mainly captures the existence of the speculative attack in favor of the Peso that occured in December, 1994.

In order to calculate the maximum differential with the AR(1) Markov processes, we need to generalize the model further. Because of the existence of two regimes, there will be two $V(.)$ functions, one for each state. The equations we iterate over to find such functions are described in the appendix. The maximum differential is given by the $V(.)$ function that exists in the tight monetary policy state, and vice-versa for the minimum differential.[22] The yield curve equation also changes, incorporating the possibility of instant capital gains when a change of state occurs, producing two different curves depending upon the state. The appendix also presents the equations needed to calculate long-term bond prices.

The static solution to calculate the maximum differential simply distributes the entry cost k proportionally over an ex-ante fixed investment horizon. Thus, the maximum differential critically depends on the assumption held regarding the duration of the investment. Of course, this estimation does not consider the implied option values, the reinvestment possibilities, and the stochastic interest-rate process. Moreover, the static solution radically violates the predictions of the expectations hypothesis of the yield curve.

The implicit tax per unit of time can be calculated as:[23]

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equivalent of the parameters. Unfortunately, likelihood ratio tests are invalid when comparing the simple and Markov AR(1) processes. Under the null hypothesis, the Markov AR(1) parameters are not identified.

[21] The annual equivalent of a monthly ω is $\exp\{12\ln(\omega)\}$, the annual equivalent of a monthly σ is $\sigma\sum_{t=0}^{11}\exp(-\frac{t\omega}{11})$, and the annual equivalent of the transition probability p is $\exp\{12\ln(p)\}$.

[22] Because transition probabilities are quite large, the two $V(.)$ functions are similar.

[23] See, e.g., Valdés-Prieto and Soto (1996) and Cárdenas and Barrera (1997).

$$Tax(M) = \frac{URR \times \ln(1 + r^{*}) \times HP}{(1 - tax) \times M}$$

where URR is the URR rate, HP is the holding period, and M is the maturity of the operation. Thus, if one assumes a short-run operation with a fixed horizon, the implicit tax that investors pay is higher. In turn, the maximum interest rate differential for a bond with maturity in $t + M$ is given by $Tax(M)$ because the domestic return given by $(r - Tax(M))M$ cannot be larger than the international return, which is equal to $r^{*}M$. Finally, the minimum differential in this static set-up cannot be less than zero.

Using the parameters of table 4 one can calculate the effect of the Chilean URR on the maximum sustainable interest rate differentials in the various models. We assume that the international interest rate is 6% and that the domestic long-run rate is equal to the international rate in both the simple AR(1) model and the loose monetary policy regime in the AR(1) Markov model. Table 5 presents the results for instantaneous, 3-, 6-, and 12-month differentials. Figure 2 shows the complete yield-curve for each model.

The results show three interesting facts. First, the results generated by the dynamic model using the four stochastic processes are considerably different from the results of the static model. While the latter predicts a maximum sustainable differential of 10.4% in 3-month operations, the former predicts a range between 1.3% to 2.6%. The difference is larger for shorter maturities. Second, the results with the four estimated stochastic processes are quite similar. With the exception of the Markov AR(1) real differential, the other three models generate very similar maximum yield curves. Third, a URR of 30% with a 1-year holding period produces a relatively modest interest rate differential. Considering the three most similar estimates, the 3-month differential would be approximately 2.3%. For 12-month operations this differential is only 1.25%. It is interesting to note that actual differentials have not been much bigger than this. In fact, the larger number in the two differential series is approximately 6% (real differential in 1993), while differentials are almost always smaller than 3.5%. The difference is explained by the effect of other capital controls and country risk (and domestic currency depreciation in the case of the real differential).

5 Concluding Remarks

This paper has presented a model for evaluating the effect of irreversible inflow and outflow payments on interest rate differentials. Since various capital control measures can be thought of as fixed proportional entry and exit taxes, one can use the model to assess the quantitative impact of such controls. In particular, it is possible to calculate maximum and minimum sustainable differentials —differences in yields which do not trigger massive capital flows— for bonds with different maturities.

The model takes into account that payments are irreversible and that entry and exit decisions are part of a dynamic optimization problem. Thus, the investment horizon is an endogenous variable that depends on the present and expected future state of the economy. Maximum and minimum sustainable differentials depend on the size of controls and on the characteristics of the stochastic process followed by differentials. For example, a higher variance and a higher degree of mean reversion produce a wider band for differentials on short-run operations in which no capital movements occur.

The numerical results show that a URR of 30% with 1-year holding period produces only modest sustainable differentials (with parameters estimated for the Chilean economy). These results are considerably larger if one considers a static model in which the investment horizon is fixed. For instance, for 3-month notes the estimated differentials are 2.3% and 10.4%, respectively. The difference is even larger for shorter maturities. These dramatic differences in sustainable differentials have important implications for assessing the effectiveness of capital controls. In particular, if policy makers overestimate the effect of controls, they may pursue policies that make the control seem ineffective.

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Appendix: 2-State Recursion

The existence of two regimes in the AR(1) Markov case modifies the equations presented in section 3.2. We now have two $V(.)$ functions, one for each state. Letting 1 and 2 denote the two states, and if P_j the probability of staying in state j after one year, we can define $V(\rho, j)$ as the value of a license to invest in Chile when the economy is in state j. To find $V(\rho, j)$, $j = 1, 2$, we iterate over the following set of equations:

$$\begin{aligned}\hat{V}_i(\rho,1) = \quad & (\rho - r^*)\tau + e^{-(r^*-\rho)\tau}[e^{-\beta_1\tau}\{q(\rho,1)V_i(\rho+\varepsilon,1) + (1-q(\rho,1))V_i(\rho-\varepsilon,1)\} \\ & +(1-e^{-\beta_1\tau})\{q(\rho,2)V_i(\rho+\varepsilon,2) + (1-q(\rho,2))V_i(\rho-\varepsilon,2)\}],\end{aligned}$$

$$\begin{aligned}\hat{V}_i(\rho,2) = \quad & (\rho - r^*)\tau + e^{-(r^*-\rho)\tau}[e^{-\beta_2\tau}\{q(\rho,2)V_i(\rho+\varepsilon,2) + (1-q(\rho,2))V_i(\rho-\varepsilon,2)\} \\ & +(1-e^{-\beta_2\tau})\{q(\rho,1)V_i(\rho+\varepsilon,1) + (1-q(\rho,1))V_i(\rho-\varepsilon,1)\}],\end{aligned}$$

$$V_{i+1}(\rho,1) = \min\langle \max\langle 0, \hat{V}_i(\rho,1)\rangle, k\rangle, \text{ y}$$

$$V_{i+1}(\rho,2) = \min\langle \max\langle 0, \hat{V}_i(\rho,2)\rangle, k\rangle,$$

where β_j is the instantaneous probability of changing state given by $-\ln(P_j)$, $j = 1, 2$, and where the probabilities of the binomial process of each state are given by:

$$q(\rho, j) = \frac{1}{2}\left[1 + \frac{w(\bar{\rho}_j - \rho)\tau}{\varepsilon}\right],$$

with $\bar{\rho}_j$ as the long-run interest rate in state j.

The price of bonds of different maturities also depends on which state the economy is in. We iterate over:

$$\begin{aligned}P(\rho, t-\tau, T, 1) = \quad & e^{-\rho\tau}[e^{-\beta_1\tau}\{q(\rho,1)P(\min\langle\rho+\varepsilon, R_1\rangle, t, T, 1) + (1-q(\rho,1)) \\ & P(\max\langle\rho-\varepsilon, r_1\rangle, t, T, 1)\} + (1-e^{-\beta_1\tau})\{q(\rho,2) \\ & P(\min\langle\rho+\varepsilon, R_2\rangle, t, T, 2) + (1-q(\rho,2)) \\ & P(\max\langle\rho-\varepsilon, r_2\rangle, t, T, 2)\}] \text{ and}\end{aligned}$$

$$
\begin{aligned}
P(\rho, t-\tau, T, 2) = \quad & e^{-\rho\tau}[e^{-\beta_2\tau}\{q(\rho,2)P(\min\langle\rho+\varepsilon, R_2\rangle, t, T, 2) + (1-q(\rho,2)) \\
& P(\max\langle\rho-\varepsilon, r_2\rangle, t, T, 2)\} + (1-e^{-\beta_2\tau})\{q(\rho,1) \\
& P(\min\langle\rho+\varepsilon, R_1\rangle, t, T, 1) + (1-q(\rho,1)) \\
& P(\max\langle\rho-\varepsilon, r_1\rangle, t, T, 1)\}],
\end{aligned}
$$

where R_j and r_j are the maximum and minimum instantaneous interest rates in state j.

Table 1: Differentials with Various Parameter Values (percentage)

	Minimum	— Maximum Sustainable —			
	Instantaneous	Instantaneous	3-months	6-months	12-months
Baseline case	–3.51	3.64	2.31	1.80	1.19
$\sigma = 0.03$	–2.81	2.92	2.06	1.68	1.20
$w = 0.05$	–3.42	3.55	2.26	1.77	1.17
$\bar{\rho} = r^* + 0.015$	–3.68	3.41	2.13	1.65	1.09
URR rate = 20%	–2.94	3.04	1.85	1.36	0.80
Exit cost = 0.01	–3.89	4.06	2.47	1.98	1.36

Baseline case parameters: $\sigma = 0.04212$, $w = 0.3216$, $r^* = 6\%$, $\bar{\rho} = r^*$, URR rate = 30%, $r^* = 6\%$, Exit cost = 0.

Table 2: Simple AR(1) Process Estimation

	Covered Differential Weekly Data Jan. 1994 – Aug. 1996	Real Differential Monthly Data Jan. 1991 – Aug. 1996
α	0.2234	0.1470
	(0.0951)	(0.1385)
ω	0.9098	0.9670
	(0.0361)	(0.0323)
σ	0.4597	0.3059
$\bar{R}^2$	0.829	0.934
Log likelihood	–85.50	–13.98

Standard errors in parenthesis.

Table 3: Markov AR(1) Process Estimation

	Covered Differential Weekly Data Jan. 1994 – Aug. 1996	Real Differential Monthly Data Jan. 1991 – Aug. 1996
α_1	0.2718	0.1832
	(0.0991)	(0.1412)
α_2	0.8403	0.6032
	(0.2555)	(0.1790)
ω	0.8771	0.8905
	(0.0407)	(0.0373)
σ	0.4396	0.2391
	(0.0291)	(0.0220)
p_1	0.9860	0.9057
	(0.0171)	(0.0651)
p_2	0.7377	0.9681
	(0.2231)	(0.0317)
Log likelihood	–84.66	–7.12
$\alpha_1 - \alpha_2$	–0.5686	–0.4200
	(0.2207)	(0.0780)

Standard errors in parenthesis.

Table 4: Parameters in Annual Base

	Covered Differential		Real Differential	
	AR(1)	AR(1) Markov	AR(1)	AR(1) Markov
$\bar{D}_2 - \bar{D}_1$	–	0.5686	–	0.4200
ω	0.0073	0.0011	0.3216	0.2486
$\sigma(\times 100)$	4.9697	3.5080	4.2120	1.5710
p_1	–	0.4813	–	0.3057
p_2	–	0.0000	–	0.6778
Months in 1	–	16.4	–	10.1
Months in 2	–	0.7	–	30.9

Table 5: URR Maximum Sustainable Differential (percentage)

	Instantaneous	3-month	6-month	12-month
Covered AR(1)	3.97	2.60	2.02	1.33
Real AR(1)	3.64	2.31	1.80	1.19
Covered AR(1) Markov	3.14	2.18	1.77	1.24
Real AR(1) Markov	1.80	1.35	1.16	0.90
Static Solution	∞	10.50	5.12	2.53

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