Monetary Conditions Indices and the Term Structure of Interest Rates

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Abstract

A monetary conditions index is a weighted average of an interest rate and an exchange rate. This paper introduces a model for pricing interest rate and exchange rate contingent claims when a central bank uses open market operations to keep a monetary conditions index inside a band. The model is applicable to Canada and New Zealand, where the central banks conduct monetary policy with the (intermediate) objective of achieving a desired level of a monetary conditions index. The model is calibrated to New Zealand data and the consequences for the behaviour of the domestic yield curve are investigated. Possibilities for improved management of interest rate and exchange rate risk are demonstrated.

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1 Introduction

The Bank of Canada introduced the concept of a Monetary Conditions Index (MCI) and has used one as an operational target for the past several years.[1] The Reserve Bank of New Zealand (RBNZ) began using an MCI as an operational target in late 1996. An MCI is a weighted average of an interest rate and an exchange rate, with the weights on the two variables chosen to reflect the estimated relative effects of the two variables on aggregate demand over some time period, typically approximately two years.[2] Targeting an MCI is an appealing generalization of interest rate targeting, as it provides the central bank with a convenient means of adjusting interest rates in response to exchange rate movements. When the central bank adopts an MCI as an operational target, movements in the domestic yield curve become inextricably linked to movements in the exchange rate. The consequences of this behaviour for asset pricing have not been investigated until now. This paper introduces a general model for pricing interest rate and exchange rate contingent claims in such an environment, and demonstrates its usefulness, both in analyzing the behaviour of the domestic yield curve and in managing interest rate and exchange rate risk.

In New Zealand, as explained by Guthrie and Wright [17], the ever-present threat of central bank intervention ensures that, at all points in time, the market will deliver a three-month interest rate equal to the level preferred by the central bank. The level of the three-month interest rate which is preferred by the RBNZ depends on the prevailing level of the exchange rate. In fact, the RBNZ has estimated that a two percentage point depreciation of the currency must be offset by a one percentage point rise in the three-month interest rate if future inflation is to be unaffected. Therefore, rather than announcing its preferred level of the three-month rate at each point in time, the RBNZ periodically announces the desired level of its MCI — a weighted-average of the three-month bank bill rate and a trade-weighted exchange rate index. Given the RBNZ's desired level of the MCI and the observed exchange rate, the market can infer the central bank's desired level of the three-month rate. The threat of central bank intervention ensures that the market delivers this three-month rate. Consequently, the central bank's threat ensures that the market delivers the desired level of the MCI.

In reality, of course, changes in the MCI only indicate approximate changes in future inflation. For this reason, the RBNZ tolerates a range of monetary conditions, only intervening when the MCI deviates from the preferred level by some critical amount. In its December 1997 Monetary Policy Statement [21, p. 40], the RBNZ states

> "...it is clear that deviations from desired monetary conditions can be very large indeed without threatening either edge of our inflation target if those deviations are of relatively short duration. This suggests that the Bank should be relatively tolerant of quite large deviations from desired

[1] Ericsson, et al. [12] describe how the MCI is constructed and used by the Bank of Canada.
[2] Difficulties in calculating these weights are discussed in [9].

> (conditions). On the other hand, large deviations, even for relatively short periods, may raise doubts ... that the Bank ... may have changed its view of desired conditions. These doubts can create uncertainty, and that uncertainty has real costs, both short-term and long-term."

The MCI is not used mechanically, but is cross-checked against other types of information and is subject to judgement by senior management. The RBNZ [21, pp. 40–41] stresses

> "As a very approximate guideline, we would expect actual monetary conditions to be within a range of plus or minus 50 (basis) points from desired in the weeks immediately following a comprehensive inflation projection. As more data comes to hand over the ensuing three months ... we may be rather more tolerant. But this is not, repeat not, a binding rule which the market can expect us to follow under all circumstances, and those expecting us to do so are likely to be disappointed."

Some features of the implementation of monetary policy, as described above, stand out. Firstly, domestic interest rates are market-determined, adjusting to incorporate new information as it becomes publicly available. Secondly, as explained in [17], interest rates evolve as if the central bank is using open market operations to influence the instantaneous interest rate. Finally, the central bank conducts monetary policy in order to defend a target zone for an MCI. These features do not appear in existing asset pricing models. The purpose of this paper is to introduce a new asset pricing model which incorporates, at the most fundamental level, certain key features of the New Zealand experience.

The simplest asset pricing models follow what could be called the 'partial-equilibrium' approach, in which model-makers specify a stochastic process for the prices of some fundamental assets and price other assets assuming that arbitrage opportunities do not exist. The most famous example of this approach is the Black-Scholes option pricing model [3], in which the price of the underlying asset follows a geometric Brownian motion. A similar approach has been adopted in an enormous array of models of the term structure of interest rates. Stochastic processes, typically for the instantaneous interest rate, but sometimes for other variables too, are chosen in order to capture regularities evident in observed interest rates, such as mean-reversion [24] or unpredictable discrete jumps in interest rates [1, 23].

These models typically ignore the underlying causes of changes in asset prices and interest rates, such as actions by monetary authorities.[3] Researchers have recently begun to incorporate central bank behaviour into their asset pricing models. The first signs of this change in approach can be found in the exchange rate target zone literature, in which central banks act to keep the exchange rate within a particular interval. This literature was initiated by Krugman [19], who analyzed the dynamics of exchange rates when a central bank uses infinitesimal interventions to defend an exchange rate target zone. That is, the central bank holds the money supply

[3] However, the effect of monetary policy on asset prices has been investigated in the Lucas class of general equilibrium models. See, for example, [4, 5].

constant as long as the exchange rate is inside the allowable band. However, if the exchange rate ever starts to move outside this band, the central bank intervenes, adjusting the money supply by the smallest amount necessary to move the exchange rate back inside the band. Krugman's model was subsequently extended to price currency options and other currency derivatives [7, 8, 10]. Svensson has studied the implications of exchange rate targeting for domestic interest rates [22].

In Krugman's model, the central bank intervenes to change an exchange rate. A small, but growing, literature investigates the consequences when the central bank intervenes to change an interest rate. Farnsworth and Bass [13] show how to apply arbitrage asset pricing principles when the monetary authority sets targets for interest rates which it enforces through direct market intervention. Babbs and Weber [2] construct a term structure model which captures, in an idealized form, some important features of the interest rate regimes in France, Germany, the United Kingdom and the United States. In their model, the central bank announces floors and ceilings for a particular interest rate at which it will immediately intervene in the market. The central bank can send signals about future levels of interest rates by changing floor and ceiling rates. Babbs and Webber model the floor and ceiling rates as jump processes and suppose they apply to the instantaneous interest rate. El-Jahel, Lindberg and Perraudin [11] also incorporate the interest rate targeting behaviour of a central bank in their models.

There are thus models in which the central bank targets the exchange rate, keeping it in a band using infinitesimal interventions. There are also models in which the central bank targets a benchmark interest rate, keeping it in a band using infinitesimal interventions. This paper models asset prices assuming the central bank targets an MCI, intervening when necessary to keep it in some preferred range. As long as this MCI is inside its band, which is assumed fixed, and publicly-known, the central bank leaves markets to determine the domestic instantaneous interest rate. If the MCI ever moves outside its band, the central bank will intervene, using open market operations to change the instantaneous rate by the smallest amount necessary to ensure the MCI does not breach the target zone. Another possibility, considered in a separate paper [16], is that the central bank intervenes to shift the exchange rate, rather than the instantaneous interest rate, whenever the MCI moves outside its target zone. Although this is not relevant for the New Zealand situation, modelling it is an interesting problem in its own right.

The current state of the economy in this model is described completely by the current levels of two state variables: the domestic instantaneous interest rate and the exchange rate. The foreign interest rate is assumed constant. This assumption is made purely to simplify the calculations involved in computing asset prices. A stochastic foreign interest rate could easily be incorporated, but at the cost of greater computational effort. Asset prices are assumed to be arbitrage-free, and are calculated using the equivalent martingale measure.

The most restrictive assumption made in the model is that there is a fixed, publicly-known and rigorously-defended target zone for the MCI. This is at odds with the current policy of the RBNZ. As highlighted earlier, the precise position of the MCI's target zone, if an explicit target zone actually exists, is not public information, except possibly during the period immediately following the release of the Bank's comprehensive inflation projections. This paper does not pretend to model every nuance of monetary policy implementation in New Zealand. Rather, it is a first step towards a model which incorporates all features of the RBNZ's behaviour. Just as Krugman's exchange rate target zone model has been extended to allow for realignment risk, this model can be extended to allow for realignments of the target zone for the MCI. Such an extension will be a focus of future research. This incremental approach has the advantage that the effects of different aspects of the RBNZ's behaviour can be isolated.

This paper examines the relationship between the exchange rate and the term structure of domestic interest rates when the central bank targets an MCI. The yield curve is found to behave in a manner which cannot be described by simple models. For example, changes in domestic interest rates of all maturities are positively correlated with changes in the domestic instantaneous interest rate, but the strength of the correlation falls as maturity rises. Changes in long-term interest rates are more positively correlated with changes in the exchange rate than are changes in short-term interest rates. That is, the correlation coefficient is an increasing function of maturity. The influence of exchange rate movements on the domestic yield curve has profound implications for the volatility of domestic interest rates. Volatility is a non-monotonic function of maturity, decreasing for short maturities, but increasing for long maturities. This paper provides some theoretical evidence for the debate about the effect of targeting an MCI on interest rate volatility. For a realistic choice of parameters, short-term interest rate volatility actually rises when the central bank widens its band for the MCI; long-term interest rates become less volatile. For practitioners, the model introduced here offers the prospect of improved management of interest rate and exchange rate risk in an environment where the central bank targets an MCI.

Formal testing of the model presented in this paper will be the subject of future research. However, many of the stylized facts evident from an inspection of Table 1 are captured by this model. The table reports summary statistics of movements in the New Zealand yield curve. At least for maturities up to three months, changes in interest rates of different maturities are positively correlated, and the strength of the correlation is a decreasing function of the difference in maturities. Furthermore, the correlation between changes in interest rates and changes in the exchange rate appears to be an increasing function of maturity. Interest rate volatility is a decreasing function of maturity.

The next section introduces the asset pricing model, beginning by describing the evolution of the state variables and how they are affected when the central bank defends its target zone. The partial differential equation which determines asset prices is presented in the second part of this section. A specific example is introduced in Section 3 and calibrated to New Zealand data. The behaviour of the yield curve in this model is analyzed in Section 4. This section includes a discussion of the factors affecting yields of different maturities and the impact tightening the band for the MCI has on the volatility of domestic interest rates. Section 5 demonstrates the potential uses of this model in managing interest rate and exchange rate risk.

Table 1: Summary statistics

	r_{Call}	$r_{\text{1-month}}$	$r_{\text{3-month}}$	$r_{\text{5-year}}$	s
Std dev	0.0229	0.0161	0.0163	0.0123	0.0574
Corr$[r_{\text{Call}}, \cdot]$	1.00	0.54	0.44	0.09	0.07
Corr$[r_{\text{1-month}}, \cdot]$		1.00	0.94	0.44	0.37
Corr$[r_{\text{3-month}}, \cdot]$			1.00	0.51	0.41
Corr$[r_{\text{5-year}}, \cdot]$				1.00	0.26

The table gives the annualized standard deviations of, and the simple correlation coefficients between, the daily changes in the indicated variables. The data set spans the period from January 3, 1996 until October 24, 1997. r_{Call} is the overnight cash rate, $r_{\text{1-month}}$ and $r_{\text{3-month}}$ are bank bill rates of the indicated maturities and $r_{\text{5-year}}$ is the five-year government bond yield. s is the natural logarithm of the reciprocal of the trade-weighted exchange rate index.

The final section offers suggestions for future research and concludes the paper.

2 A General Asset Pricing Model

Consider an economy in which the central bank targets the MCI $m = R - \alpha s$, where R denotes the T_0-year interest rate, s is the (natural logarithm of the) exchange rate (measured as the domestic price of foreign currency) and α is a constant. The central bank uses infinitesimal interventions, adjusting the domestic instantaneous interest rate, when required to prevent the MCI from falling below some lower bound $\underline{m}$ and from climbing above some upper bound $\overline{m}$. That is, if the MCI ever falls below $\underline{m}$, the central bank will immediately increase the instantaneous interest rate just enough to move the MCI back to $\underline{m}$. Similarly, the central bank will immediately reduce the instantaneous interest rate if the MCI ever climbs above $\overline{m}$, adjusting it by the smallest amount necessary to defend the ceiling. The level of these bounds is assumed to be constant and is public information.

At time t, the state of the economy is assumed to be described completely by the level of the domestic instantaneous interest rate r_t and the exchange rate s_t. When the central bank is not intervening to defend the target zone for its MCI, the dynamics of the state variables under the equivalent martingale measure are described by

$$dr_t = \mu_1(r_t, s_t, t)dt + \sigma_1(r_t, s_t, t)d\xi_t, \quad ds_t = (r_t - r_f)dt + \sigma_2(r_t, s_t, t)d\zeta_t.$$

$d\xi_t$ and $d\zeta_t$ are increments of Wiener processes, with $E[(d\xi_t)(d\zeta_t)] = \rho dt$, and μ_1, σ_1 and σ_2 are arbitrary functions. The foreign interest rate r_f is assumed to be constant. The MCI being targeted by the central bank is a function of the two state variables. Let the MCI at time t equal $m_t = M(r_t, s_t, t)$. As long as $\underline{m} < m_t < \overline{m}$, the central bank leaves the instantaneous interest rate to evolve according to the process above. From Itô's Lemma, the MCI evolves according to

$$dm_t = \mu_m dt + \sigma_1 M_r d\xi_t + \sigma_2 M_s d\zeta_2,$$

where

$$\mu_m = \mu_1 M_r + (r - r_f)M_s + \frac{1}{2}\sigma_1^2 M_r^2 + \rho\sigma_1\sigma_2 M_r M_s + \frac{1}{2}\sigma_2^2 M_s^2.$$

Suppose, however, that the MCI is at the bottom of the band; that is, $M(r, s, t) = \underline{m}$. If, during the next time increment, the shocks to the two state variables are such that the change in the MCI is positive ($dm > 0$), the central bank does nothing, allowing the MCI to move back inside the band of its own accord. However, if the shocks would, other things being equal, lead to a lower value of the MCI ($dm < 0$), the central bank will respond by adjusting the domestic instantaneous interest rate. If the central bank increases the instantaneous interest rate by an amount dx, the MCI will increase by $dm + M_r dx$ in total. Therefore, by increasing the instantaneous rate by the amount $dx = -dm/M_r$, the central bank ensures that the MCI remains equal to $\underline{m}$. Combining the two possible outcomes, when the MCI is at the bottom of the central bank's target zone, it increases the domestic instantaneous interest rate by the amount

$$dx = \frac{1}{M_r} \max\{0, -dm\}.$$

Since dm is normally distributed with mean $\mu_m dt$ and standard deviation $\sigma_m \sqrt{dt}$, where

$$\sigma_m^2 = \sigma_1^2 M_r^2 + 2\rho\sigma_1\sigma_2 M_r M_s + \sigma_2^2 M_s^2,$$

the expected change in the domestic instantaneous interest rate equals

$$E[dx | M(r, s, t) = \underline{m}] = \frac{\phi(a)\sigma_m}{M_r} \cdot \sqrt{dt} - \frac{\Phi(a)\mu_m}{M_r} \cdot dt. \tag{1}$$

ϕ is the density function for the standard normal distribution, Φ is the distribution function and $a = -\mu_m \sqrt{dt}/\sigma_m$.[4] A similar argument shows that

$$E[dx | M(r, s, t) = \overline{m}] = \frac{-\phi(a)\sigma_m}{M_r} \cdot \sqrt{dt} - \frac{(1 - \Phi(a))\mu_m}{M_r} \cdot dt.$$

The Local Expectations Hypothesis holds under the equivalent martingale measure. That is, the price at time t of an asset with a single payoff of $g(r_T, s_T)$ at time $T \geq t$ is given by

$$F(r_t, s_t, t) = E_t \left[\exp\left(-\int_t^T r_u du \right) g(r_T, s_T) \right]. \tag{2}$$

It is the expected discounted value of the future payoff, where the discount rate to be used at each instant is the prevailing instantaneous interest rate. Therefore, the current price of an asset equals the expected value, under the equivalent martingale measure, of the price in the next time increment, discounted at the current instantaneous interest rate. It is easily shown that this implies $E[dF] = rF dt$.

[4] This calculation uses the well-known properties of the truncated normal distribution as described in, for example, Johnson and Katz [18, p. 81].

Asset prices can be found by solving a partial differential equation. As long as $\underline{m} < M(r, s, t) < \overline{m}$, the stochastic process generating the state variables is not regulated by the central bank. Itô's Lemma shows that the expected return from holding the asset over the next time increment equals

$$E[dF] = \left(F_t + \mu_1 F_r + (r - r_f)F_s + \frac{1}{2}\sigma_1^2 F_{rr} + \rho\sigma_1\sigma_2 F_{rs} + \frac{1}{2}\sigma_2^2 F_{ss}\right) dt.$$

If the expected rate of return is to equal r, F must satisfy the partial differential equation

$$0 = F_t + \mu_1 F_r + (r - r_f)F_s + \frac{1}{2}\sigma_1^2 F_{rr} + \rho\sigma_1\sigma_2 F_{rs} + \frac{1}{2}\sigma_2^2 F_{ss} - rF \qquad (3)$$

whenever $\underline{m} < M(r, s, t) < \overline{m}$. The situation is more complicated when the MCI is at either edge of its target zone. For example, equation (1) shows that the expected change in r is of order $O(\sqrt{dt})$ along the lower boundary of the MCI's target zone. Unless $F_r = 0$ there, the expected change in the asset's price will also be of order $O(\sqrt{dt})$.[5] If this was the case, $E[dF]/dt$ would be unbounded as $dt \to 0$, indicating that arbitrage opportunities exist when the MCI is at the lower boundary of its target zone. A similar argument shows that F_r must vanish whenever $M(r, s, t) = \overline{m}$. Therefore,

$$F_r(r, s, t) = 0 \text{ whenever } M(r, s, t) \in \{\underline{m}, \overline{m}\}. \qquad (4)$$

These "smooth-pasting" conditions are analogous to the boundary conditions familiar from the work of Dixit [6] and many others. Finally, when $t = T$, equation (2) collapses to

$$F(r, s, T) = g(r, s). \qquad (5)$$

The price $F(r, s, t)$ of the asset can be found by solving the partial differential equation (3), together with the smooth-pasting conditions (4) and the terminal condition (5). This problem is solved over the region in (r, s)-space with boundaries $M(r, s, t) = \underline{m}$ and $M(r, s, t) = \overline{m}$.[6]

[5]From equation (1),

$$E[dF|M(r, s, t) = \underline{m}] = F_r(r, s, t)\frac{\phi(a)\sigma_m}{M_r} \cdot \sqrt{dt} + O(dt),$$

where the term $O(dt)$ involves first and second order derivatives of F.

[6]These boundaries must be known before solving for the asset price function F. However, the boundaries depend on the MCI, which depends (through the T_0-year rate) on bond prices. Bond prices and the boundaries are found simultaneously by solving a complicated free boundary value problem. Let $B(r, s, t; T)$ equal the price at time t of a discount bond paying one dollar at time T. Then the MCI equals $(-1/T_0)\log B(r, s, t; t + T_0) - \alpha s$ at time t. B must satisfy the partial differential equation

$$0 = B_t + \mu_1 B_r + (r - r_f)B_s + \frac{1}{2}\sigma_1^2 B_{rr} + \rho\sigma_1\sigma_2 B_{rs} + \frac{1}{2}\sigma_2^2 B_{ss} - rB,$$

whenever $\underline{m} < (-1/T_0)\log B(r, s, t; t + T_0) - \alpha s < \overline{m}$, together with the terminal condition $B(r, s, T, T) = 1$ and the smooth-pasting conditions $B_r = 0$ when $(-1/T_0)\log B(r, s, t; t+T_0) - \alpha s = \underline{m}$ and $(-1/T_0)\log B(r, s, t; t + T_0) - \alpha s = \overline{m}$.

Further progress requires some parameterization of the general framework described thus far.

3 An Example

The remainder of this paper considers, in detail, a special case of the general model introduced above. In this example, as long as the central bank is not defending its target zone for the MCI, the instantaneous interest rate evolves according to a simple Brownian motion without drift: $dr_t = \sigma_1 d\xi_t$, for some constant σ_1. The exchange rate is generated by the stochastic process

$$ds_t = (r_t - r_f)dt + \sigma_2 d\zeta_t,$$

with $E[(d\xi_t)(d\zeta_t)] = \rho dt$, for some constants ρ and σ_2.[7]

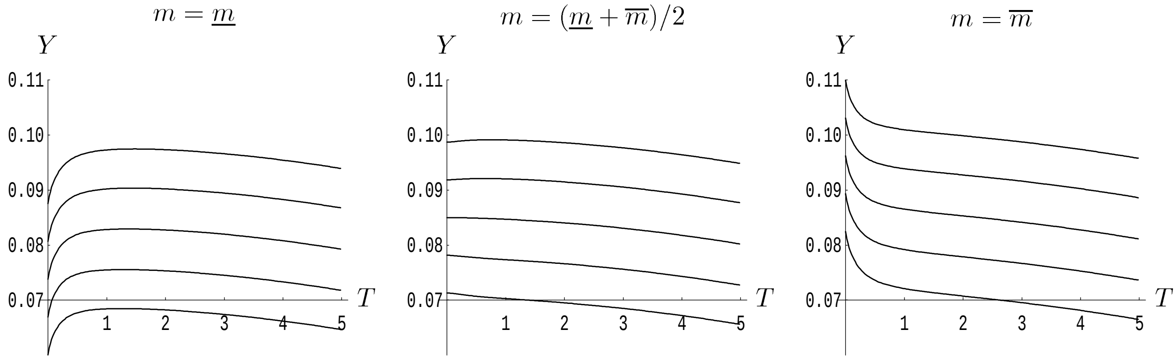
Even with such a simple stochastic process generating the state variables, numerical techniques are required to solve equations (3), (4) and (5). Specific values of all parameters must be chosen. A crude calibration to New Zealand data is achieved by choosing parameters motivated by the summary statistics reported in Table 1. The instantaneous interest rate is assumed to have volatility $\sigma_1 = 0.02$, which is approximately the annualized standard deviation of daily changes in the call rate. The volatility of the exchange rate is set equal to $\sigma_2 = 0.06$, approximately equal to the annualized standard deviation of daily changes in the trade-weighted exchange rate index. Except where the effect of varying ρ is explicitly investigated, changes in the two state variables are assumed to be uncorrelated ($\rho = 0$). The foreign interest rate is set equal to 0.085. The central bank monitors the MCI $m = R - \alpha s$, where $\alpha = 0.5$ and R is the three-month interest rate ($T_0 = 0.25$). A target zone of $[0.08, 0.09]$ is assumed.

A crucial step in solving the model is identifying the region in (r, s)-space to which the central bank must, if it is to successfully defend the target zone for its MCI, restrict the state variables. For the calibration described above, this region was found to be approximately the set of states (r, s) for which $0.0713 \leq r - s/2 \leq 0.0987$. That is, given an exchange rate of s, the central bank must ensure the instantaneous rate never falls below $s/2 + 0.0713$, nor climbs above $s/2 + 0.0987$. The simplicity of this rule is the principal reason for choosing such simple stochastic processes for the two state variables. Other processes would potentially lead to more complicated regions in (r, s)-space, making solution of the partial differential equation even more difficult.

Equation (3), together with the associated boundary conditions, was solved for bond prices over the region $0.0713 \leq r - s/2 \leq 0.0987$, using the calibration just described. The Crank-Nicholson implicit finite difference method was used to solve the partial differential equation. The properties of these solutions are examined in the following section.

[7]This process for the instantaneous rate was first used by Merton [20] in his term structure model. Standard currency option pricing models, such as those by Garman and Kohlhagen [14] and Grabbe [15], assume the same volatility structure for changes in the exchange rate.

Figure 1: Typical yield curves



Each plot shows the range of yield curves (with maturity measured in years) possible for a particular level of the MCI. The MCI is at the bottom of the band in the left plot, in the middle of the band in the middle plot and at the top of the band in the right plot. The state variables evolve according to processes with $\sigma_1 = 0.02$, $\sigma_2 = 0.06$, $\rho = 0$ and $r_f = 0.085$. The MCI has $T_0 = 0.25$ and $\alpha = 0.5$. It is restricted to the interval $[0.08, 0.09]$.

4 Yield Curve Analysis

From equation (2), the price of a discount bond equals the expected discounted value of a fixed future payoff, where the rate of discount to be used at each instant is the prevailing instantaneous interest rate. Domestic interest rates are therefore determined solely by the distribution of the instantaneous interest rate over the lifetime of the corresponding discount bond. When the central bank targets an MCI, this distribution depends on the exchange rate, as well as the current level of the instantaneous interest rate. Thus, movements in the domestic yield curve are inextricably linked to movements in the exchange rate. The nature of the relationship is explored in this section. It begins by describing the relationship between the level of the MCI and the shape of the yield curve. The second part discusses the differing roles of the instantaneous interest rate and the exchange rate in determining domestic interest rates. Finally, the implications for the volatility of domestic interest rates are examined.

4.1 Shape of Yield Curves

If $B(r_t, s_t, t; t+T)$ equals the price at time t of a bond paying one dollar at time $t+T$, then the T-year rate at time t equals

$$Y(r_t, s_t, t; T) = (-1/T) \log B(r_t, s_t, t; t+T).$$

Figure 1 shows the different yield curves possible in this model. Each graph shows a range of yield curves, corresponding to different levels of the instantaneous interest rate, for a common level of the MCI. The MCI is at the bottom of its target zone

($m = \underline{m}$) in the graph on the left and at the top ($m = \overline{m}$) in the graph on the right. In the central graph, the MCI is midrange ($m = (\underline{m} + \overline{m})/2$). It is clear from Figure 1 that the level of the yield curve is determined by the level of the instantaneous interest rate, while the shape of the yield curve is determined by the position of the MCI in its band.

The central bank will not allow monetary conditions to tighten further when the index is at the top of its target zone. In the immediate future, monetary conditions will either loosen, or they will not change. Thus, the instantaneous interest rate will tend to fall in the immediate future, since any increase will tend to be reversed as the central bank defends its target for the MCI, while any reduction in the instantaneous rate will not trigger any response from the central bank. Long-term interest rates will reflect this downward trend in the expected instantaneous rate — the yield curve will be downward-sloping. When the MCI is at the bottom of the central bank's target zone, the yield curve will be hump-shaped. The central bank will reverse any further loosening of monetary conditions, so that, in the immediate future, monetary conditions will either tighten, or they will not change. The instantaneous interest rate will be expected to increase in the immediate future, as the central bank will tend to reverse any reduction in the instantaneous rate and will not respond to any rise. Anticipating this, markets deliver an upward-sloping yield curve, at least for short maturities.[8]

4.2 Determinants of Yields

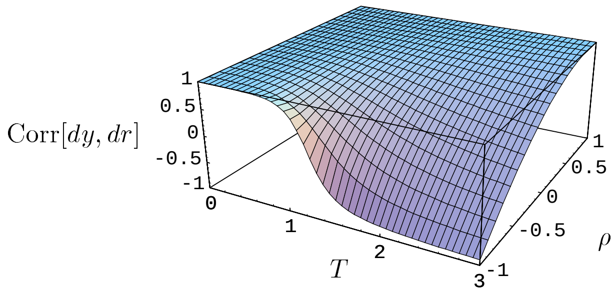
The relative influence of the instantaneous interest rate and the exchange rate on domestic interest rates depends on the maturities of the interest rate in question and the position of the MCI in its target zone.

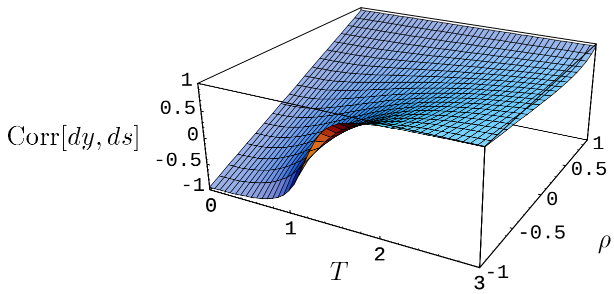
The domestic instantaneous interest rate evolves according to a simple Brownian motion. Its movements are bounded above and below by barriers, the position of which depends on the level of the exchange rate. As long as the instantaneous rate is away from these barriers, there is a negligible probability that it will be adjusted by the central bank in the immediate future. Therefore, the principal determinant of the distribution of the instantaneous rate in the short-term is the current level of the instantaneous rate; the barriers, and hence the current level of the exchange rate, are unimportant. However, the current level of the instantaneous rate has almost no effect on its distribution in the distant future. The long-run distribution of the instantaneous rate is determined, not by its current value, but by the position of the barriers. This, in turn, is determined by the current level of the exchange rate.

Increasing the current instantaneous rate shifts the distribution of the instantaneous rate, at all times in the future, to the right. However, the effect diminishes as the forecast horizon increases. Therefore, if the instantaneous interest rate rises, domestic interest rates of all maturities will also increase. Long-term rates will respond less than short-term rates and none will increase by more than the instantaneous

[8]The yield curve eventually slopes downwards. This is not due to any anticipated fall in the instantaneous interest rate in the distant future. Rather, it is a consequence of choosing a process for which the instantaneous rate can become negative with positive probability.

Figure 2: Term structure of correlation coefficients





The top plot shows Corr$[dy, dr]$, the correlation between changes in yields of various maturities and changes in the instantaneous interest rate as a function of maturity (measured in months) and the correlation between changes in the two state variables. The bottom plot shows Corr$[dy, ds]$, the correlation between changes in yields of various maturities and changes in the exchange rate. All correlation coefficients are calculated at the point where $r = r_f = 0.085$ and $s = 0$. The state variables evolve according to processes with $\sigma_1 = 0.02$, $\sigma_2 = 0.06$ and $\rho = 0$. The MCI has $T_0 = 0.25$ and $\alpha = 0.5$. It is restricted to the interval $[0.08, 0.09]$.

rate. If the currency depreciates, the distribution of the instantaneous rate, at all times in the future, shifts to the right. The effect increases as the forecast horizon increases. Therefore, if the exchange rate rises, domestic interest rates of all (non-zero) maturities will also increase. Long-term rates respond more than short-term rates.

Movements in the yield curve are therefore driven by two factors. One, r, determines short-term interest rates. The other, s, determines long-term interest rates. As maturity increases, the influence of r diminishes, and that of s grows. This can be seen in Figure 2, which shows the correlation between changes in the state variables and movements in the yield curve. The top graph plots Corr$[dy, dr]$, where y is a domestic interest rate, as a function of maturity and ρ. The correlation between changes in domestic interest rates and changes in the domestic instantaneous interest rate is seen to be a decreasing function of maturity. The bottom part of the figure displays the correlation between changes in domestic interest rates and changes in the exchange rate, again, as a function of maturity and ρ. The correlation is an increasing function of maturity, with changes in very long-term interest rates perfectly positively correlated with changes in the exchange rate. When the two state variables are strongly negatively correlated ($\rho \approx -1$), the transition occurs very rapidly, shown in the figure by the rapid reduction in Corr$[dy, dr]$ and the rapid increase in Corr$[dy, ds]$. For less extreme levels of ρ, the transition is more gradual.

The relative influence of r and s can also be seen in Figure 3, which displays the contours of yields of various maturities as functions of r and s. The central bank uses its ability to control the domestic instantaneous interest rate in order to keep the state variables between the broken lines in each figure. The solid curves represent contours of the indicated domestic interest rate — any two points on the same curve represent states with the same level of the indicated interest rate. Away from the edges of the target zone, contours of short-term interest rates are almost vertical straight lines. That is, the level of these interest rates is determined by the level of r. The level of the exchange rate is irrelevant. As maturity increases, the yield contours grow flatter — the influence of the exchange rate strengthens. The contours of the five-year rate are almost indistinguishable from horizontal straight lines, confirming that the level of the exchange rate is all important and that of the instantaneous interest rate is all but irrelevant.

This behaviour changes when the MCI is near either edge of the central bank's target zone. At the bottom of the target zone, for example, the central bank will not allow the MCI to fall any lower. Reductions in the instantaneous interest rate will tend to be reversed by the central bank; increases will not be reversed. Investors can confidently predict that the instantaneous rate will rise, not fall, corresponding to a small move to the right in (r, s)-space. However, the contours of interest rates of all maturities are horizontal near the broken lines in Figure 3. This ensures that these small predictable movements have no effect on longer-term interest rates. Therefore, investors can not use the predictable changes in the instantaneous interest rate which occur when the MCI is near either edge of the target zone to exploit arbitrage opportunities. Interest rates of all maturities are determined by the level of the exchange rate when the MCI is near either edge of the target zone.

4.3 Interest Rate Volatility

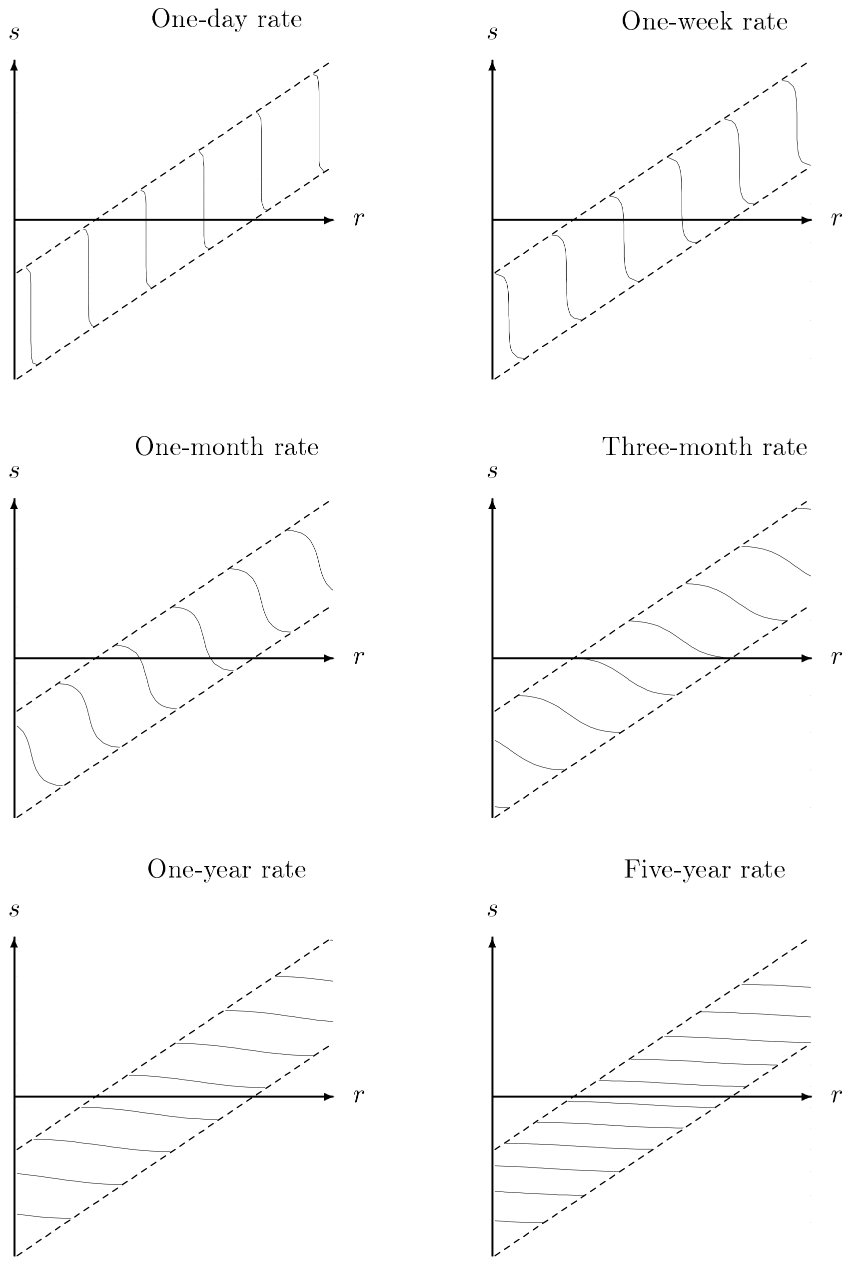
The volatility of a domestic interest rate depends on its sensitivity to changes in the two state variables. This sensitivity has been seen to depend on the maturity of the interest rate. This section considers the resulting relationship between maturity and volatility. It also investigates the relationship between interest rate volatility and the width of the target zone for the MCI.

The instantaneous variance of changes in y, the T-year interest rate, equals

$$V = \frac{E[(dy)^2]}{dt} = \sigma_1^2 Y_r^2 + 2\rho\sigma_1\sigma_2 Y_r Y_s + \sigma_2^2 Y_s^2.$$

This expression admits a natural decomposition into three components. The first, $\sigma_1^2 Y_r^2$, reflects the sensitivity of the T-year rate to changes in the domestic instantaneous interest rate; the second component, $\sigma_2^2 Y_s^2$, arises due to the sensitivity of

Figure 3: Contour plots



Each plot shows the contours of the indicated interest rate as a function of r (horizontal axis) and s (vertical axis). The state variables evolve according to processes with $\sigma_1 = 0.02$, $\sigma_2 = 0.06$, $\rho = 0$ and $r_f = 0.085$. The MCI has $T_0 = 0.25$ and $\alpha = 0.5$. It is restricted to the interval $[0.08, 0.09]$.

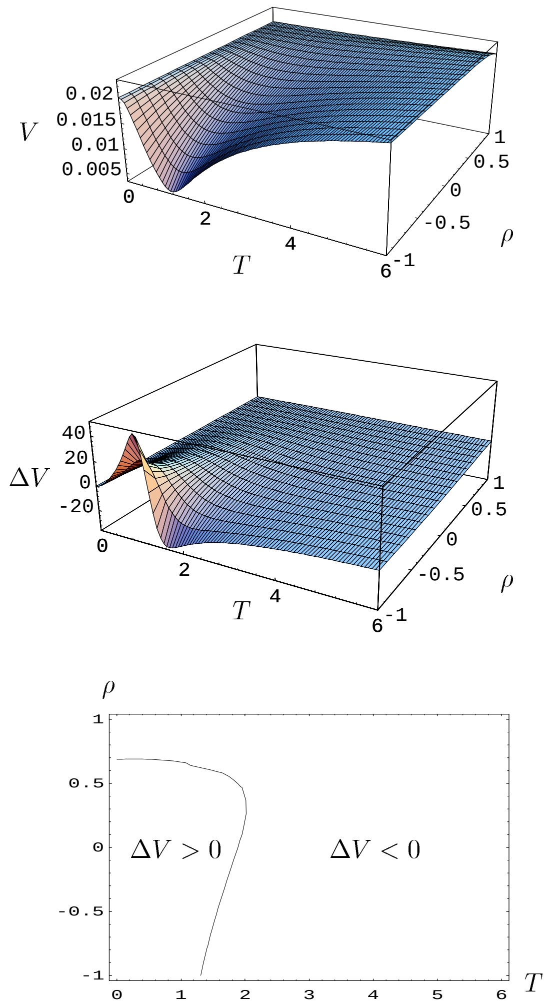
the T-year rate to changes in the exchange rate; the third component, $2\rho\sigma_1\sigma_2 Y_r Y_s$, reflects the fact that the two state variables, to a greater or lesser extent, move together. As maturity increases, sensitivity to the instantaneous rate falls (Y_r falls), so the first component diminishes. The second component increases in stength, as interest rates become more sensitive to changes in the exchange rate (Y_s increases), as maturity increases. Finally, consider the third component of yield volatility. Suppose that changes in the state variables are negatively correlated, so that increases in the instantaneous interest rate tend to be associated with reductions in the exchange rate and vice versa. A higher instantaneous interest rate leads to higher interest rates of all maturities, but a currency appreciation leads to lower interest rates of all maturities. Thus, the negative correlation between changes in the state variables has a stabilizing effect on domestic interest rates. In this situation, the third component of yield volatility is negative. In general, it has the same sign as the correlation coefficient for changes in r and s.

The top graph in Figure 4 plots volatility as a function of maturity (measured in months) and the correlation between changes in the two state variables when the MCI is in the middle of its target zone. Provided changes in these two variables are not perfectly positively correlated, volatility first falls as maturity increases, then rises. The initial reduction in volatility is especially pronounced when the state variables exhibit strong negative correlation. The offsetting effects of interest and exchange rate shocks lead to relatively stable interest rates with maturities up to two months.

A popular criticism of targeting an MCI is that it encourages the central bank to react too quickly in response to exchange rate movements. According to this argument, domestic interest rates adjust immediately following any shock to the exchange rate, in order to keep the MCI inside its target zone. The stochastic process driving domestic interest rates is thus augmented by the, usually more volatile, stochastic term driving the exchange rate. This, so the argument proceeds, makes domestic interest rates excessively volatile. However, this is an overly simplistic view, because targeting an MCI influences the volatility of domestic interest rates through three distinct channels.

Suppose the band for the MCI is widened, so that the central bank is more tolerant of deviations from its preferred level of monetary conditions. As the barriers restricting the movement of the instantaneous rate move apart, the current level of the instantaneous rate plays a greater role in determining its future distribution. For a given maturity, this increases the sensitivity of domestic interest rates to changes in the instantaneous rate and reduces their sensitivity to changes in the exchange rate. The volatility of short-term rates is dominated by the first effect, and so increases. However, the second effect dominates for long-term interest rates, causing the volatility of these interest rates to fall. This behaviour is confirmed in the bottom two graphs in Figure 4. They plot the percentage increase in volatility (denoted by ΔV), as a function of maturity and the correlation between changes in the state variables, when the width of the target zone is increased by 10%. The bottom graph breaks (T, ρ)-space into regions where volatility falls ($\Delta V < 0$) and where it rises ($\Delta V > 0$). Unless changes in the state variables are strongly positively

Figure 4: Term structure of volatilities



The top plot shows the volatility of domestic interest rates as a function of maturity (measured in months) and the correlation between changes in the two state variables. The second figure shows the percentage change in volatility following a widening of the target zone by 10%. The bottom plot displays the combinations of maturity (measured in months) and ρ for which widening the target zone reduces interest rate volatility ($\Delta V < 0$) and for which it increases interest rate volatility ($\Delta V > 0$). All volatilities are calculated at the point where $r = r_f = 0.085$ and $s = 0$. The state variables evolve according to processes with $\sigma_1 = 0.02$, $\sigma_2 = 0.06$ and $\rho = 0$. The MCI has $T_0 = 0.25$ and $\alpha = 0.5$. It is restricted to the interval $[0.08, 0.09]$.

correlated, increasing the width of the target zone actually leads to greater volatility in short-term interest rates. Interest rates with maturities greater than two months become less volatile.

5 Implications For Risk-Management

This section considers the implications of targeting an MCI for risk-management. It begins by examining the risks associated with holding portfolios of some vanilla interest rate and exchange rate derivatives. Optimal hedging strategies can only be determined once these risks have been identified.

Consider an asset or portfolio which has value $v_t = V(r_t, s_t, t)$ at time t. The economy is subject to two different types of shock. Over a time period of length dt, the shock to the instantaneous interest rate is normally distributed with mean zero and standard deviation $\sigma_1\sqrt{dt}$, while the shock to the exchange rate is normally distributed with mean $(r_t - r_f)dt$ and standard deviation $\sigma_2\sqrt{dt}$. For the calibration featured here ($\sigma_1 = 0.02$ and $\sigma_2 = 0.06$), the 95% confidence interval for the daily change in the instantaneous rate is approximately ± 25 basis points, while the equivalent interval for the daily change in the exchange rate is approximately ± 75 basis points. The second and third columns of Table 2 report $V_r dr/V$ and $V_s ds/V$, respectively, where $dr = 25$ basis points and $ds = 75$ basis points. The first number is the percentage increase in the value of the indicated asset following a 25 basis point rise in the instantaneous interest rate; the second number is the percentage increase in the asset's value following a 75 basis point depreciation of the exchange rate.[9]

The first feature to note is the significant sensitivity of coupon bond prices to exchange rate shocks. For example, if the exchange rate depreciates by two daily standard deviations, the price of a ten-year coupon bond falls by more than 5%. This feature cannot be captured by standard term structure models, since, in these models, exchange rate movements do not, by themselves, affect domestic bond prices. The second class of assets considered is put options on domestic bonds. Standard bond option pricing models display the extreme sensitivity of domestic bond option prices to movements in the domestic instantaneous interest rate evident from the second column, but they cannot generate the extreme sensitivity of these options' prices to changes in the exchange rate. Notice that for bond put options close to expiry, exchange rate shocks have almost twice the effect of comparable shocks to the instantaneous interest rate. When the expiry date of the put option is distant, interest rate shocks have slightly greater effect than exchange rate shocks. Finally, interest rate shocks lead to substantial swings in currency put option prices (of the order of $\pm 1\%$), but these are dwarfed by the effect of shocks to the exchange rate. As the maturity date approaches, the sensitivity of currency put option prices to interest rate shocks falls, while the sensitivity to exchange rate shocks rises, not surprisingly, since foreign currency is the underlying asset.

These few examples demonstrate the insights this model can provide into the

[9] Actually, this is not quite true, since $V_r dr$ and $V_s ds$ are only an adequate approximation of the changes in V for small changes dr and ds. The approximation is unreliable for large changes, such as the indicated ± 25 and ± 75 basis points. This explains why, for instance, a currency put option, at-the-money, with one week until expiry, appears to fall in value by more than 100% following a 75 basis point depreciation of the exchange rate. Nevertheless, reporting the sensitivities in this form facilitates comparisons between the state variables and between assets.

Table 2: Implications for risk-management

Security	Sensitivities		Replicating portfolio		
	r	s	H_B	H_C	H_M
Discount bonds					
One-week	−0.01	0.00	0.1587	0.0096	0.8333
One-month	−0.02	0.00	0.5488	0.0278	0.4280
Three-month	−0.03	−0.05	1.0000	0.0000	0.0000
Six-month	−0.04	−0.14	1.2115	−0.1080	−0.1196
Coupon bonds					
Three-year	−0.10	−1.47	3.1765	−1.7507	−0.3693
Five-year	−0.16	−2.64	4.9474	−3.2405	−0.5967
Ten-year	−0.28	−5.25	10.5006	−7.7885	−1.2861
In-the-money bond put options					
One-week	36.89	64.80	−0.6673	0.0097	0.6442
One-month	26.30	35.86	−0.6568	−0.0016	0.6454
Three-month	22.06	17.21	−0.7647	−0.0212	0.7710
At-the-money bond put options					
One-week	51.10	92.10	−0.4430	0.0073	0.4266
One-month	31.22	42.68	−0.5141	−0.0012	0.5050
Three-month	24.44	19.07	−0.6528	−0.0181	0.6581
Out-of-the-money bond put options					
One-week	71.57	138.96	−0.2191	0.0049	0.2097
One-month	36.95	50.73	−0.3718	−0.0008	0.3651
Three-month	27.04	21.10	−0.5412	−0.0150	0.5454

The sensitivities give the percentage change in the price of the particular asset following a two standard deviation daily change in the appropriate state variable. That is, the instantaneous interest rate increases by 25 basis points and the exchange rate depreciates by 0.75%. The portfolio comprising H_B three-month discount bonds, H_C units of foreign currency and H_M dollars in a domestic money-market account replicates the indicated security.

risks associated with holding interest rate and exchange rate derivatives. The appropriate hedges are also easily extracted from the model. Since the current state of the economy is described completely by the current values of two state variables, the payoff of any portfolio of risky assets can be replicated by investing in a combination of three different assets. For example, a replicating portfolio might involve holdings of domestic three-month discount bonds, foreign currency and investment in a domestic money market account earning interest at the instantaneous rate. Consider the portfolio comprising H_B three-month discount bonds (each worth $B(r_t, s_t, t)$ dollars at time t), H_C units of foreign currency (each worth e^{s_t} dollars at time t) and H_M dollars invested in the domestic money market account. This portfolio has value

$$B(r_t, s_t, t)H_B + e^{s_t}H_C + H_M \tag{6}$$

at time t and increases in value by

$$B_r(r_t, s_t, t)H_B dr_t \tag{7}$$

Table 2: Continued

Security	Sensitivities		Replicating portfolio		
	r	s	H_B	H_C	H_M
In-the-money currency put options					
One-week	−0.26	−36.96	0.1609	−0.9757	0.8381
One-month	−0.77	−31.08	0.4982	−0.8383	0.3715
Three-month	−1.04	−23.43	0.7796	−0.7147	−0.0241
At-the-money currency put options					
One-week	−0.76	−109.39	0.0801	−0.4924	0.4174
One-month	−1.30	−54.21	0.2756	−0.4791	0.2162
Three-month	−1.36	−31.92	0.5045	−0.4822	0.0004
Out-of-the-money currency put options					
One-week	−1.70	−255.00	0.0017	−0.0112	0.0095
One-month	−1.79	−87.95	0.0574	−0.1185	0.0634
Three-month	−1.63	−42.47	0.2330	−0.2477	0.0243

1. Coupon bonds pay interest semi-annually at the rate of 8% per annum.
2. In-the-money bond puts have exercise price $K = 0.9795$, or a yield of 8.3%; at-the-money puts have exercise price $K = 0.9790$, or a yield of 8.5%; out-of-the-money puts have exercise price $K = 0.9785$, or a yield of 8.7%. The underlying asset is a three-month discount bond.
3. In-the-money currency puts have exercise price $K = 1.02$; at-the-money puts have exercise price $K = 1.00$; out-of-the-money puts have exercise price $K = 0.98$.
4. All options are European.

All sensitivities are calculated at the point where $r = r_f = 0.085$ and $s = 0$. The state variables evolve according to processes with $\sigma_1 = 0.02$, $\sigma_2 = 0.06$ and $\rho = 0$. The MCI has $T_0 = 0$ and $\alpha = 0.5$. It is restricted to the interval $[0.08, 0.09]$.

if the instantaneous rate experiences a shock of dr_t, and by the amount

$$(B_s(r_t, s_t, t)H_B + e^{s_t} H_C)ds_t \tag{8}$$

if the currency depreciates by the proportion ds_t. If expressions (6) to (8) equal $V(r_t, s_t, t)$, $V_r(r_t, s_t, t)dr_t$ and $V_s(r_t, s_t, t)ds_t$, respectively, this portfolio behaves exactly the same as the asset which has value $V(r_t, s_t, t)$ at time t. Provided the portfolio comprises

$$H_B = \frac{V_r(r_t, s_t, t)}{B_r(r_t, s_t, t)}$$

three-month discount bonds,

$$H_C = e^{-s_t}\left(V_s(r_t, s_t, t) - \frac{V_r(r_t, s_t, t)B_s(r_t, s_t, t)}{B_r(r_t, s_t, t)}\right)$$

units of foreign currency and

$$H_M = V(r_t, s_t, t) - V_s(r_t, s_t, t) - \frac{V_r(r_t, s_t, t)}{B_r(r_t, s_t, t)}(B(r_t, s_t, t) - B_s(r_t, s_t, t))$$

dollars invested in the domestic money market account, this will indeed be the case. The fourth, fifth and sixth columns of Table 2 report these replicating portfolios for a variety of assets.

Notice that foreign currency holdings play a significant role in replicating domestic bonds. In the case of a ten-year coupon bond with principal of \$1, for example, the replicating portfolio comprises 10.5 domestic three-month discount bonds, funded by borrowing \$1.29 on the domestic overnight market and another \$7.79 sourced from overseas. Foreign currency holdings play an insignificant part in replicating domestic bond options. This is surprising, considering the extreme sensitivity of bond option prices to exchange rate shocks. The reason can only be that the three-month discount bonds appearing in the replicating portfolio capture most of the exchange rate risk. Only very small foreign currency holdings are needed to 'fine-tune' the replicating portfolio.

Recall that the prices of currency put options are relatively insensitive to domestic interest rate shocks. It is surprising, therefore, to see that holdings of domestic three-month discount bonds play such a significant role in replicating currency put options. To a greater or lesser extent, replicating a currency put option involves short-selling foreign currency, as seen by the negative entries in the fifth column of Table 2. The proceeds of these short-sales are invested almost entirely in domestic three-month discount bonds when the option's expiry date is distant. As the expiry date nears, these funds are shifted from three-month discount bonds to the domestic money market account. This can be seen in columns four and six of Table 2, where H_B falls as the expiry date approaches, while H_M increases.

6 Conclusion

This paper has introduced an asset pricing model for economies in which the central bank targets an MCI. Even for the very simple stochastic process chosen here, targeting an MCI leads to a complicated relationship between movements in the domestic yield curve and the exchange rate. The model introduced in this paper can be used, as in the first part of Section 5, to analyze the risks associated with holding particular portfolios. The assets in these portfolios are not restricted to the vanilla options considered in Table 2, but can be any asset with a payoff contingent on the exchange rate and the domestic yield curve. In addition, as in the second part of Section 5, the model can be used to replicate such portfolios using primitive assets (such as domestic bonds, foreign currency and the domestic money market account) and eliminate the risks they pose. The model offers the prospect of improved risk-management in an environment in which the central bank defends a target zone for an MCI.

The model can be extended in a variety of ways. Alternative processes for the existing state variables can easily be incorporated. Another straightforward alteration would be to incorporate a stochastic foreign interest rate. Asset prices would then be sensitive to a third source of risk — foreign interest rate shocks — so that replicating portfolios would need to comprise four, rather than three, different assets. A convenient choice would be domestic and foreign three-month discount bonds and domestic and foreign money market accounts, earning interest at the domestic and foreign instantaneous interest rates, respectively.

A more significant extension would be to relax the assumption that the desired level of the MCI is constant. Krugman's exchange rate target zone model was subsequently extended to incorporate stochastic realignments in the target zone. Similar techniques should be applicable to the model introduced in this paper. The work by Babbs and Weber [2] might provide a good starting point. They modelled central bank-imposed floors and ceilings on the instantaneous interest rate and allowed the floor and ceiling to evolve according to a pure jump process. A similar approach could be applied to the boundaries of the MCI's target zone.

Finally, the manner in which the central bank intervenes when its target is threatened could be modified. In the model presented here, when the band is threatened, the central bank acts so as to return the MCI to the edge of the target zone. Another possibility is that when the central bank intervenes, it will return the MCI to the middle of the target zone. This can be modelled by solving the same partial differential equation, but with suitably altered boundary conditions. The implications of this alternative policy for the behaviour of the domestic yield curve are being investigated.

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