Market-Implemented Monetary Policy with Open Mouth Operations

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Abstract

This paper explains how financial markets can be used to implement monetary policy on behalf of the monetary authority. A model is presented where, despite policy settings being held constant, markets deliver interest rates as though the central bank was using open market operations to achieve them. If interest rates move out of line with those required by the monetary authority, a statement (an open mouth operation) is all that is needed to restore them. We explain how the current implementation of monetary policy in New Zealand works in this way. Using announcement data from New Zealand, we find that open mouth operations lead to large changes in interest rates across all maturities, and these changes cannot be explained by open market operations. Implications are drawn for monetary policy more generally.

[JEL: E42, E52, E58]

1 Introduction

In the recent literature on optimal central bank design, New Zealand's approach to targeting inflation has been the subject of much analysis.[1] For instance, Persson and Tabellini (1993) and Walsh (1995a, 1995b) look at how central bankers' incentives should be structured, arguing that the New Zealand Reserve Bank Act comes closest to the optimal structure; Svensson (1997) derives the form of the optimal inflation target when monetary policy is delegated to the central bank, where delegation is along the lines of the New Zealand regime; and Ammer and Freeman (1995) and McCallum (1996) discuss the merits of New Zealand's inflation-targeting regime. In contrast, another unusual feature of New Zealand's monetary policy design, its implementation, has gone virtually unnoticed.[2]

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[1]This approach can be summarized as: (a) the government assigns an explicit inflation target; (b) the central bank is given independence to achieve this target; (c) if the target is not met, the government requires an explanation from the Bank and has the option of dismissing the Bank's governor.

[2]Exceptions are McCallum (1995), as noted below, and Archer (p.11, 12, and 15, 1997).

As with a number of other countries (Australia, Belgium, Canada, Netherlands, Sweden and the United Kingdom), New Zealand has no reserve requirements. Without reserve requirements, the demand for reserves is essentially a demand for settlement cash balances (commercial bank reserves held with the central bank to be used for the settlement of payments). Central banks can exercise control over short-term interest rates by controlling the supply of these settlement cash balances through open market operations. However, despite having the ability to influence interest rates through this mechanism, the central bank in New Zealand does not use open market operations to control interest rates. Instead, open market operations are used to target a constant daily level of settlement cash balances. The level of this target is the key policy instrument of New Zealand's monetary authority, the Reserve Bank of New Zealand (RBNZ). As McCallum (1995, p. 19) points out, it is very rarely changed:

> "*An unusual feature of the New Zealand practice is that the RBNZ in fact alters the settlement cash target very infrequently. But the fact that it can affect the interbank rate if it so chooses is sufficient to induce this rate to adjust as desired by the RBNZ. Normally all that is needed, evidently, is for the RBNZ to communicate its intentions to participants in the interbank market.*"

In effect, the central bank of New Zealand targets a very narrow version of the money stock on a day-to-day basis, keeping this target constant for long periods.[3] Despite this, market interest rates evolve as if the central bank is using open market operations to achieve these rates. Market rates occasionally deviate from the levels the central bank believes are appropriate. When these deviations are sufficiently large, interest rates are brought back into line by the Bank's public statements. This paper provides a theory explaining how interest rates can adjust automatically and why public statements are sometimes needed.

We develop a model in which the central bank threatens to use open market operations to influence the overnight interest rate if a single interest rate (for example, the three-month rate) deviates from the central bank's preferred level. The preferred level is that which the central bank thinks is most appropriate, given its objectives, out of the range of interest rate levels it could achieve using standard open market operations. Borrowers will not borrow at higher rates, and lenders will not lend at lower rates, since to do so would lead to a capital loss. The threat ties down this single interest rate. The threat of future open market operations ties down the expected value of future levels of this rate. Then the expectations hypothesis, along with a technical assumption discussed in Section 2, ties down current rates of all maturities. As long as the threat is credible, the threatened open market operations need not occur. Instead, the central bank keeps policy settings constant. To do this, and ensure money market equilibrium is maintained at all times, the central bank automatically accomodates any change in money demand with an equal

[3] Ignoring three earlier changes in the target, which lasted for one day only and were not used to alter monetary conditions, and a technical change which took place along with other changes on February 22nd, 1991, there have been only three episodes when the cash target has been changed during our sample period (January 1989 to September 1997): an increase in the target on September 25th, 1991, a decrease on January 6th, 1993 which was fully reversed by February 3rd, 1993, and two decreases in August 1995.

change in the monetary base. We illustrate, with two examples, how this can be achieved using a mechanical rule.

In the first example, the central bank offers to lend to (and borrow from) households with the interest rate set automatically to the corresponding market rate. Under this set-up, money market equilibrium holds at all times, and the monetary base becomes endogenous to movements in the nominal demand for money. In the second example, we provide a model which matches the set-up in New Zealand. This extends the previous example by introducing a demand for cash by banks, who need it to settle their accounts with the government each day. The key features of this set-up are that the RBNZ uses open market operations solely to target a constant nominal stock of settlement cash balances, keeps deviations from this target within a constant level of forecast accuracy (in nominal terms), and pays interest on settlement cash and charges a discount rate, both of which move automatically with market rates. We show that these features ensure banks are willing to hold the constant stock of settlement cash at market-implemented interest rates and that the monetary base remains endogenous to movements in the nominal demand for money by households.

The design of monetary policy implementation in New Zealand suggests that a useful way to think about market-implemented monetary policy more generally is to imagine a central bank split into two divisions: "financial markets" and "monetary policy." Each day in the financial markets division, the Bank mechanically injects or withdraws cash through open market operations according to some rule, without regard to the objectives of monetary policy. Meanwhile, in the monetary policy division, policy makers form a view on the appropriate level of interest rates. Monetary policy is market-implemented if the financial markets division and the monetary policy division can be run independently, with no communication between them, and yet interest rates evolve as if the monetary policy division is directing the financial markets division on appropriate open market operations. Only if the threat to change policy instruments is carried out does the monetary policy division actually need to direct the financial markets division what to do. However, this is not to say that the monetary policy division is unnecessary. Without the threat of intervention, which stems from the monetary policy division forming a view about appropriate monetary conditions, there is nothing to tie down the level of interest rates and prices in this framework.

Since, with market-implemented monetary policy, the market delivers the interest rate it believes the central bank prefers, new information which affects the central bank's preferred monetary conditions is incorporated into market interest rates as it becomes publicly available. This assumes that the private sector knows the central bank's preferred interest rate at all times. In reality, the central bank's interpretation of new information is not public knowledge and the market does not know the bank's preferred monetary conditions exactly. There is thus no guarantee that the market will deliver the interest rate that the central bank actually prefers. By making an announcement, the central bank can signal its preferred interest rate. The market will move the interest rate to the preferred level. We develop a model in which central bank announcements are costly, as are deviations from its preferred level of the interest rate. When choosing the timing of announcements, the central bank faces an optimization problem similar to the classical inventory problem. An (S, s)-policy is optimal — the central bank will only make costly announcements when the discrepancy between its views and those of the private sector moves outside a particular band. These are the "open mouth operations" referred to in the title of the paper.

An important implication of market-implemented monetary policy with open mouth operations is that when the central bank makes an announcement, this represents a surprise to the private sector. If the market knew that the central bank wanted a change in the interest rate, the market would already have delivered the change. Moreover, because announcements are only made when the discrepancy between the private sector's and the bank's view of the appropriate interest rate falls outside a band, interest rates will jump following announcements. We test these implications using announcements of the RBNZ, reported by Reuters and codified by us, together with daily financial data from January 1989 to September 1997. Consistent with the theory, we find that announcements are unpredictable and that they do indeed cause interest rates to jump. Moreover, using data on variations in actual cash settlement balances caused by exogenous daily forecast errors of the RBNZ, we show that the movement in interest rates following announcements is not caused by open market operations.

We think such a monetary framework is of interest outside New Zealand for two primary reasons. The first centers on the potential advantages such a framework offers. One possible advantage is that monetary policy can, more often than not, be implemented without politically-sensitive changes in interest rate targets, thus avoiding the usual tendency to delay or soften necessary changes in monetary conditions. To the extent this makes monetary policy more credible, it lowers the costs of achieving and maintaining price stability. Another possible advantage of the approach arises if it allows the monetary authority to communicate its intentions to the market better than a traditional framework. Goodfriend (1991) suggests that, in a traditional framework, the monetary authority smooths short-term interest rates so as to present markets with a clear path of future rates. The expectations hypothesis then ties down longer-term rates, the rates the monetary authority actually cares about. In New Zealand's framework, the central bank can, if needed, focus directly on longer-term rates.

The second reason to be interested in New Zealand's method of monetary policy implementation is the implications it has for research into monetary policy. For instance, open mouth operations provide us with a unique "news" study of monetary policy. According to our theory, announcements in New Zealand, unlike announcements of changes in the federal funds rate target in the United States, represent pure surprises to market participants. Thus, in contrast to Federal Reserve target changes, Reserve Bank announcements provide a clean measure of a change in monetary policy stance, relative to market expectations. Another research agenda raised by this paper is to explore the possibility open mouth operations play a role in monetary policy implementation in countries other than New Zealand. The idea is that open market operations influence short-term interest rates in part through the signal associated with these actions. While the use of such signals differs widely across countries, in all cases the credibility and effectiveness of the signal depends on the ability of the central bank to threaten to dry up or flood the market for bank reserves. In this regard, New Zealand's use of open mouth operations under market-implemented monetary policy can be viewed as a case study, albeit an extreme one, of what occurs in central banks elsewhere.

The remainder of the paper proceeds as follows. Section 2 presents our theory of market-implemented monetary policy, providing two examples of how it can be put into practice. Section 3 explains why announcements (open mouth operations) are sometimes needed and proceeds to model them formally. The data and codification of open mouth operations is described in Section 4. Section 5 provides an empirical investigation of open mouth operations. Finally, Section 6 concludes, with some further implications for monetary policy.

2 Market-Implemented Monetary Policy

The starting point for our analysis is a traditional approach to monetary policy implementation, in which the central bank uses open market operations to influence nominal short-term interest rates over time, so as to best achieve its inflation (and possibly output) objectives. This section shows how the central bank can achieve the same outcome without having to use open market operations to influence rates. This relies on the central bank having a credible threat (which ties down the level of interest rates), as well as a mechanism to ensure money market equilibrium is automatically maintained at these market-delivered interest rates.

Our theory will apply under a wide variety of macro models. A key requirement is that the central bank can achieve its inflation objectives by treating a nominal interest rate as its instrument.[4] Of course, there are distinct views on why interest rates can be used as an instrument to achieve the Bank's inflation objectives. According to a monetarist view, the central bank targets a particular level of interest rates because, in order to achieve that level, the Bank must adjust the monetary base by the amount which generates the desired change in the price level. Alternatively, according to a Keynesian view, a particular level of interest rates is chosen because of its direct impact on aggregate demand, and thus the price level. The particular macro model one considers puts specific restrictions on the nature of the interest rate rules which the central bank can choose. In particular, restrictions will typically be required so that nominal variables are uniquely determined. However, we simply take it as given that some appropriately restricted interest rate rule exists.[5]

[4] It must also be the case that the implied path of the monetary base required to implement this interest rate rule in the traditional approach can be uniquely determined from the money market equilibrium condition.

[5] Sargent and Wallace (1975) first showed, in a simple rational expectations model, that interest rate rules could lead to an indeterminate price level. McCallum (1981) proved this not to be the case, provided the interest rate rules depend on some nominal variable. However, Kerr and King (1996) have shown, in a variety of macro models where aggregate demand depends on expected future output, even this restriction is not sufficient to uniquely determine a price level. They find that if the monetary authority responds to deviations of the inflation rate from a target path, the monetary authority must make the nominal interest

To present the basic model of market-implemented monetary policy we treat time as discrete, with the unit of measurement equalling one day. We denote by $R_{t,t+m}$ the m-day, continuously compounded, nominal interest rate prevailing on day t, and by R_t the overnight nominal rate on day t; by definition $R_t = R_{t,t+1}$. We assume that the term structure of interest rates can be described by the expectations hypothesis

$$R_{t,t+m} = \frac{1}{m}\sum_{k=0}^{m-1} E_t[R_{t+k}], \quad m \geq 1.$$

We suppose that, in order to meet its objectives, the central bank has a preferred level of the T-day rate. The preferred level is the one which the central bank thinks is most appropriate of all those it could achieve using open market operations; it must satisfy any restrictions that the economy puts on permissible interest rate rules. We let $\hat{R}_{t,t+T}$ denote the level of the T-day rate which the central bank would like to see at time t. In general, this is some complicated stochastic process which depends on the central bank's objectives, the monetary transmission mechanism, and the various shocks which impact on the economy.

Example

As an example of one such interest rate rule, consider an adapted version of a simple macro model of the economy which has been widely used.[6] The adaptation is to allow the T-day rate, rather than the overnight rate, to affect aggregate demand. The model contains a flexible-price aggregate supply relationship (only surprise changes in prices matter), aggregate demand that depends on the expectation of next period's output as well as the real T-day interest rate, a monetary authority reaction function in which the T-day interest rate reacts to deviations between inflation and the inflation objective, a Fisher equation, the expectations hypothesis, and a standard money market equilibrium condition. The details of the model and its equilibrium solution are contained in Appendix A. The monetary authority's preferred T-day rate is found to be

$$\hat{R}_{t,t+T} = r^*_{t,t+T} + \pi^* + \frac{1}{1+\psi sg}x_t + \frac{\psi g}{\lambda}u_t + \frac{\rho}{s\lambda}u_{t-1},$$

where $r^*_{t,t+T}$ is the equilibrium real T-day interest rate which is assumed to follow a random walk, π^* is the monetary authority's inflation objective, x_t is a white noise error in the monetary authority's reaction function, and u_t is an AR(1) aggregate demand shock. Note that positive aggregate demand shocks imply the central bank will want higher nominal interest rates. As in Kerr and King, the assumption that $g > 1$ ensures a unique rational expectations equilibrium exists.

We define a central bank as acting traditionally if it uses open market operations in order to set the overnight rate in such a way that market expectations will then set the

rate change by more than one-for-one with changes in the inflation rate if a unique rational expectations equilibrium is to exist. We use such a rule to illustrate the workings of market-implemented monetary policy below.

[6]Kerr and King (1996) and McCallum (1997) discuss the micro-foundations for such a model.

T-day rate at the level preferred by the central bank. That is, the central bank uses open market operations to set the overnight rate equal to some level $\hat{R}_t$ on day t, for all t, in such a way that

$$R_{t,t+T} = \frac{1}{T}\sum_{k=0}^{T-1} E_t[\hat{R}_{t+k}] = \hat{R}_{t,t+T}.$$

There are infinitely many possible paths for the overnight rate consistent with the evolution of the preferred level of the T-day rate. However, if current expectations of future preferred levels of the T-day rate converge sufficiently quickly as the forecast horizon increases, just one path for the overnight rate is expected to converge in the future. Formally, we have:

Lemma 1 *Suppose the preferred level of the T-day rate has the following property:*

$$E_t[\hat{R}_{t+n,t+n+T}] = \bar{R}_t + O(n^{-k}) \tag{1}$$

for some $k > 1$ and some $\bar{R}_t$. There exists a unique process for the overnight rate which satisfies

$$\hat{R}_{t,t+T} = \frac{1}{T}\sum_{k=0}^{T-1} E_t[\hat{R}_{t+k}] \tag{2}$$

and for which $\lim_{n\to\infty} E_t[\hat{R}_{t+n}]$ exists.
PROOF See Appendix B.1.

Therefore, provided the preferred level of the T-day rate satisfies condition (1), just one consistent path for the overnight rate converges. This is the obvious process to adopt for the overnight rate, since all others lead to non-convergent behavior in the distant future. The central bank could, if it wished, use open market operations each day in order to achieve this level of the overnight rate. This would ensure the market delivered the preferred level of the T-day rate.

Example (continued)

The preferred level of the T-day rate found in the example above converges to $\bar{R}_t = r^*_{t,t+T} + \pi^*$. Using the formula for the overnight rate, equation (20) found in the proof of Lemma 1, we see that the only consistent level of the overnight rate which is forecast to converge in the future is

$$\hat{R}_t = r^*_{t,t+T} + \pi^* + \frac{T}{1+\psi sg}x_t + \frac{T(\psi sg(1-\rho) - (\rho - \rho^T))}{s\lambda(1-\rho^T)}u_t + \frac{\rho T}{s\lambda}u_{t-1}.$$

Using the money market equilibrium condition (16) from Appendix (A), we can back out the implied rule for money growth. This is given by equation (19), which defines the traditional approach.

We show the central bank can achieve the same outcome as is achieved with this traditional approach, without having to use open market operations to influence rates. We describe this alternative mechanism below. It involves two components: an implicit threat of central bank action if the market does not deliver the central bank's preferred level of the T-day rate and some automatic mechanism to ensure money market equilibrium is maintained at market-delivered rates.

The threat involves the central bank reverting to traditional behavior, using open market operations to set the overnight rate, if markets allow the T-day rate to deviate from the central bank's preferred level. Suppose that the market delivers the wrong T-day rate on day t. Then the central bank will use open market operations on day $t+1$ to ensure that

$$R_{t+1} = \hat{R}_{t+1} + \hat{R}_t - R_t,$$

where $\hat{R}_{t+k}$ is the overnight rate the central bank would choose on day $t+k$ if it followed the traditional approach. From day $t+2$ onwards, it will use open market operations to deliver $R_{t+k} = \hat{R}_{t+k}$. An investor who purchased a T-day discount bond on day t will be left holding a $(T-1)$-day bond on day $t+1$ which is worth $\exp(-(T-1)R_{t+1,t+T})$, where

$$\begin{aligned} E_t[R_{t+1,t+T}] &= \frac{1}{T-1}\sum_{k=1}^{T-1} E_t[R_{t+k}] \\ &= \frac{1}{T-1}\left(E_t[\hat{R}_{t+1}] + \hat{R}_t - R_t + \sum_{k=2}^{T-1} E_t[R_{t+k}]\right) \\ &= \frac{1}{T-1}\left(\sum_{k=0}^{T-1} E_t[\hat{R}_{t+k}] - R_t\right) \\ &= \frac{T}{T-1}\hat{R}_{t,t+T} - \frac{1}{T-1}R_t. \end{aligned}$$

Since the bond cost $\exp(-TR_{t,t+T})$ when purchased, the investor's expected rate of return on the transaction is

$$TR_{t,t+T} - (T-1)E_t[R_{t+1,t+T}] = R_t + T(R_{t,t+T} - \hat{R}_{t,t+T}).$$

If the T-day rate is higher than the central bank's preferred level on day t, no investors will be willing to sell a T-day bond, as the expected return from holding the T-day bond overnight is higher than the expected return from holding an overnight bond. Conversely, if the T-day rate is lower than the central bank's preferred level on day t, no investors will be willing to purchase a T-day bond, as the expected return from holding the T-day bond overnight is less than the expected return from holding an overnight bond. Therefore, if markets are to clear, the T-day rate must equal the central bank's preferred level. This proves:

Proposition 1 *Suppose the central bank makes the threat described above, then the market will deliver the T-day rate equal to the central bank's preferred level.*

Carrying out this threat is costly to the central bank. If the central bank is forced to act, the market will deliver the T-day rate

$$R_{t+1,t+1+T} = \frac{1}{T}\sum_{k=1}^{T} E_{t+1}R_{t+k}$$

$$
\begin{aligned}
&= \frac{1}{T}\left(\hat{R}_{t+1} + \hat{R}_t - R_t + \sum_{k=2}^{T} E_{t+1}\hat{R}_{t+k}\right) \\
&= \hat{R}_{t+1,t+1+T} + \frac{1}{T}(\hat{R}_t - R_t),
\end{aligned}
$$

which is not equal to $\hat{R}_{t+1,t+1+T}$ in general.[7] Providing the long-run benefit of earning a reputation for carrying out its threats dominates the short-run cost to the central bank of deviating from preferred interest rate levels, the central bank's commitment will not be doubted. It will never be required to actually carry out its threat.[8]

The central bank's threat determines the T-day rate, but how are interest rates of other maturities determined? Any yield curve delivered by the market must be consistent with the expectations hypothesis, otherwise markets for bonds of some maturities will not clear. A well-known consequence of the expectations hypothesis is that forward rates equal the expected value of the corresponding future spot rates. If the ongoing threat of central bank intervention is credible, the best forecast on day t of the T-day rate n days in the future is $E_t[\hat{R}_{t+n,t+n+T}]$. This must equal the n-day ahead forward T-day rate on day t. Thus, the threat uniquely determines the forward T-day rate curve. Of course, infinitely many yield curves are consistent with a given forward T-day rate curve, so the yield curve is not uniquely determined by the threat.

Suppose, however, that the central bank's preferred level of the T-day rate converges rapidly as the forecast horizon increases, in the sense of (1). Then there is only one yield curve consistent with the forward T-day rate curve and for which the forward overnight rate curve is flat for distant horizons. Moreover, this yield curve is exactly the same as the one resulting from the traditional method of implementing monetary policy. That is:

Proposition 2 *Suppose the central bank makes the threat described above and that the market delivers a forward overnight rate curve which becomes flat at distant horizons. Further suppose the preferred level of the T-day rate satisfies property (1). Then the market will deliver exactly the same yield curve as if the central bank followed the traditional method, conducting open market operations in order to control the level of the overnight rate each day.*

PROOF See Appendix B.2.

[7] Notice, however, that the discrepancy will most likely be very small. If the central bank focuses on the three-month interest rate and is forced to carry out its threat, the three-month interest rate will deviate from the central bank's preferred level by just one ninetieth of $\hat{R}_t - R_t$ for one day only.

[8] The experience of New Zealand indicates two times over the last nine years when the central bank's commitment was tested. In both cases, the market called into question the RBNZ's credibility and the RBNZ responded by changing its settlement cash target. In practice, the delay before the RBNZ acted was greater than that modeled above, but this was compensated for by a greater punishment when the threat was carried out. For instance, after repeated warnings in the last two weeks of 1992 that the depreciation in the New Zealand dollar should be matched by firming interest rates, and with no such firming delivered by the market, the Reserve Bank cut the cash target from 20 million dollars to zero on January 7th, 1993. The deputy governor at the time, Peter Nicholl stated, "This action should unequivocally illustrate our determination." Rates quickly responded — on the same day, the cash rate increased 500 basis points, the one-month rate increased 313 basis points, and the three-month rate increased 91 basis points. The settlement cash target was returned to its original level by February 3rd, 1993.

How does this work? The central bank's threat ties down the current T-day rate. Expectations of this threat applying in the future tie down the expected level of the T-day rate in the future. Then the expectations hypothesis, together with the technical conditions outlined in Proposition 2, ensure the other rates are the same as they would be under traditional monetary policy implementation.

It remains to show how the money market can clear at these interest rates. In particular, we must show that the central bank's policy settings are consistent with the market-delivered rates. Consider the case where markets correctly believe that the central bank prefers the three-month rate to be 10%, but at the same time the central bank is allowing banks to discount as many bills as they wish at 5%. Market rates will not be sustainable at 10%. Alternatively, suppose that there is a fixed level of the monetary base. For a given price level and output level, individuals and firms will not generally be willing to hold this amount of money at the market-delivered interest rates. The central bank needs an appropriate mechanism to ensure money market equilibrium is maintained at all times. Below we provide examples of two such mechanisms. The first involves a very simple mechanism, in which the central bank offers to borrow or lend overnight, on demand, at the market overnight rate. The second builds on this principle, and models the specific mechanism used by the Reserve Bank in New Zealand. In both cases we show that, despite the fact policy settings, or more precisely the rules that govern them, remain constant, the money market is cleared for any interest rates delivered by the market.

A Simple Mechanism

We assume only households demand currency, and that they borrow and lend from the central bank directly.[9] In particular, suppose households' demand for currency takes the simple form[10]

$$M_t^d = P_t Y_t e^{-\theta R_t}, \tag{3}$$

where M_t^d is the demand for nominal money on day t, P_t is the aggregate price level on day t and Y_t is aggregate real output on day t. The monetary authority borrows and lends, on demand, for one-day periods at the market-determined overnight rate, provided it does not need to carry out its threat. The monetary base (households' holding of currency) will adjust to ensure the money market clears, despite the fact the Bank's only instrument (the overnight interest rate for borrowing from and lending to the Bank) changes automatically with market rates. Consider an increase in the central bank's preferred T-day rate which increases the overnight market rate. Households will demand less money (depositing it with the monetary authority instead), thus automatically contracting the monetary base to match the lower demand for money. If prices and output rise, households will demand more money (taking it from their holdings with the monetary authority), thus automatically expanding the monetary base to match the higher demand for money.

[9]Non-financial firms can be thought of as households, too. Financial firms are assumed to transact without currency.

[10]Note that taking logarithms of (3), we get a standard money demand function as in equation (16) of Appendix A.

With a credible threat and the above mechanism, market-implemented monetary policy delivers the same monetary growth rates and interest rates as a traditional approach. The two approaches differ only in how the central bank exercises its control. In a traditional approach, this is through the choice of open market operations. These are used to influence the overnight interest rate and, through the expectations hypothesis, the rate it actually cares about, the T-day rate. With market-implemented monetary policy, this process is essentially reversed. The central bank exercises its control directly on the T-day rate, through its implicit threat. The overnight rate is then determined by arbitrage, given the expected path of this T-day rate. The simple mechanism above ensures money growth stays consistent with these rates, so that the money market clears at all times. However, this mechanism is far simpler than that actually used in New Zealand. We now model the latter mechanism and show it also ensures the money market clears regardless of the interest rates delivered by the market.

The New Zealand Mechanism

In this example, we provide a model of monetary policy implementation in New Zealand.[11] This extends the previous example by introducing a role for banks in monetary policy implementation. Banks demand settlement cash in order to settle their accounts with the government each day. The key features are that the RBNZ uses open market operations solely to target a constant nominal stock of settlement cash balances, keeps deviations from this target within a constant level of forecast accuracy (in nominal terms), and pays interest on settlement cash and charges a discount rate, both of which move automatically with market rates. We show that these features ensure banks are willing to hold the constant stock of settlement cash at market-implemented interest rates and that the money supply remains endogenous to movements in the nominal demand for money by households. Money market equilibrium is maintained at all times.

Each day there is a net flow of funds between the government and the banking sector. This arises primarily from payments from the government to the private sector (government expenditure) and payments from the private sector to the government (tax revenue). These payments are made and received in settlement cash through the banking system. Settlement cash is simply commercial bank deposits held with the RBNZ for the settlement of such payments. We assume the net flow of funds can be described by the stochastic process

$$P_tY_t(w_t\mu_t + (1 - w_t)\varepsilon_{t+1}),$$

where μ_t represents the predicted component of this flow and ε_{t+1} is the unpredicted component; that is $E_t(\varepsilon_{t+1}) = 0$. We assume ε_{t+1} has a density function f and a cumulative distribution function F. The weight on the predicted component w_t, depends on the forecasting effort of the central bank. Each morning the RBNZ forecasts the net flow of funds between the government and the banking sector in the end of that day's settlement process. The magnitude of the net flow of funds is assumed to be proportional to nominal

[11] More extensive details of monetary policy implementation in New Zealand are contained in Huxford and Reddell (1996).

GDP (P_tY_t). Each day there is also a flow of funds between households and the banking sector. Households are assumed to want to hold cash

$$M_t^d = P_tY_te^{-\theta R_t},$$

so that the banking system gets an injection of cash from households (convertible to settlement cash) each day of

$$-\left(P_tY_te^{-\theta R_t} - P_{t-1}Y_{t-1}e^{-\theta R_{t-1}}\right).$$

If the banking system has settlement cash S_t at the beginning of day t, it will have S_{t+1} at the end of day t (before settlement), where

$$S_{t+1} = S_t + P_tY_t(w_t\mu_t + (1-w_t)\varepsilon_{t+1}) - \left(P_tY_te^{-\theta R_t} - P_{t-1}Y_{t-1}e^{-\theta R_{t-1}}\right) + v_t.$$

The term v_t represents the central bank's open market operation, which is carried out mid-morning and is designed so that the settlement cash held at the start of the next day is expected to be equal to the Reserve Bank's settlement cash target S_t^*. That is, v_t is chosen so that $E_tS_{t+1} = S_t^*$. This implies

$$S_{t+1} = S_t^* + P_tY_t(1-w_t)\varepsilon_{t+1}.$$

Notice the difference between the end-of-day settlement cash balances and the target level corresponds to the unpredicted component of the net flow of funds, $P_tY_t(1-w_t)\varepsilon_{t+1}$. For this reason we refer to this term as the Reserve Bank's settlement cash forecast error. A positive settlement cash forecast error corresponds to an injection of cash into the settlement process. A negative settlement cash forecast error corresponds to an equivalent withdrawal of cash. We will use this fact to explore the role of liquidity shocks on interest rates in Section 5.

We assume there are N identical banks. At the end of each day they must settle their accounts with the government with settlement cash; no overdraft facilities are allowed. Settlement cash earns a rate R_t^{SC}, which is below the market interest rate. If a bank falls short of settlement cash to settle its accounts it must discount Reserve Bank bills to attain additional settlement cash. However, doing so is expensive, as the discount rate R_t^D is above market rates. The settlement cash an individual bank will be holding at the end of the banking day (before settlement) will be

$$\frac{S_t^* + P_tY_t(1-w_t)\varepsilon_{t+1}}{N} + d_t, \tag{4}$$

where d_t is the amount the bank borrows in the inter-bank market to hold as additional settlement cash. If (4) is negative, the bank will have to discount Reserve Bank bills to settle its account; if (4) is positive, the bank will earn interest from the RBNZ on its holding of settlement cash. The expected dollar gain for an individual bank from borrowing d_t dollars in the inter-bank market at the daily rate of R_t is

$$E_t\pi_{t+1} = E_tV_{t+1}(d_t) - E_tV_{t+1}(0) - (1+R_t)d_t, \tag{5}$$

where

$$E_tV_{t+1}(d_t) = \int_{-\infty}^{\frac{-Nd_t - S_t^*}{P_tY_t(1-w_t)}} (1+R_t^D)\left(\frac{S_t^* + P_tY_t(1-w_t)\varepsilon_{t+1}}{N} + d_t\right) f(\varepsilon_{t+1})d\varepsilon_{t+1}$$
$$+ \int_{\frac{-Nd_t - S_t^*}{P_tY_t(1-w_t)}}^{\infty} (1+R_t^{SC})\left(\frac{S_t^* + P_tY_t(1-w_t)\varepsilon_{t+1}}{N} + d_t\right) f(\varepsilon_{t+1})d\varepsilon_{t+1}.$$

The first integral term represents the cost to a bank when it has to discount Reserve Bank bills because it is holding insufficient settlement cash. The second integral term represents the return to a bank when it does not have to discount Reserve Bank bills, since it then receives interest on positive balances. Given the interest rates in the market, the bank is assumed to choose d_t to maximize (5). The first order condition is then

$$F\left(\frac{-Nd_t^* - S_t^*}{P_tY_t(1-w_t)}\right) = \frac{R_t - R_t^{SC}}{R_t^D - R_t^{SC}}, \tag{6}$$

where d_t^* represents the solution. Recall that $R_t^{SC} < R_t < R_t^D$ and that F is a cumulative distribution function, so d_t^* is well-defined.

We first show how the monetary authority can obtain the interest rate it requires through what amounts to standard monetary policy implementation. It simply adjusts S_t^* so that[12]

$$S_t^* = -P_tY_t(1-w_t)F^{-1}\left(\frac{R_t - R_t^{SC}}{R_t^D - R_t^{SC}}\right) \tag{7}$$

This ensures the equilibrium condition $d_t^* = 0$ is met; it is not possible for all banks to be net lenders or net borrowers in the inter-bank market.[13] The left hand side of (7) is interpretable as the stock of settlement cash and the right hand side is interpretable as nominal demand for settlement cash. With a constant level of forecasting effort ($w_t = w$), the nominal demand for settlement cash can be shown to have standard properties. (To see this, note that $F^{-1}(\cdot)$ is negative.) Banks' demand for settlement cash is high when prices are high, output is high, and when the nominal interest rate is low. An increase in the settlement cash target, for a given level of prices and output, will lower the overnight interest rate. This represents the traditional approach to implementation.

We now show that equilibrium can still be maintained even if the settlement cash target remains constant ($S_t^* = S^*$). This requires a mechanism to keep the demand for holding nominal settlement cash balances equal to the constant nominal settlement cash target. This mechanism consists of two components. The first is a rule for keeping deviations from the settlement cash target within a constant level of forecast accuracy (in nominal terms). This is done by choosing its forecasting effort w_t so that the distribution of its nominal forecast error $P_tY_t(1-w_t)\varepsilon_{t+1}$ remains constant; that is,

$$w_t = 1 - \frac{\phi}{P_tY_t}, \tag{8}$$

[12]To ensure $R_t^{SC} < R_t < R_t^D$, it may also require the occasional adjustment in R_t^{SC} and R_t^D. This is again consistent with traditional monetary policy where the return on settlement cash is zero and the discount rate is occasionally adjusted to bring it into line with movements in market rates.

[13]Given that the monetary authority automatically reacts to any change in demand for money from households by conducting open market operations to offset any flows between households and banks, this condition will also ensure the money market is in equilibrium at all times.

where ϕ is some constant. In practice, the rule the RBNZ follows is to try to achieve a forecast error of 20 million dollars or less, in four days out of five. Note that this rule is indeed expressed in nominal terms. The second component to the automatic mechanism is to pay interest on settlement cash and charge a discount rate which both move automatically with market rates. This is achieved by setting R_t^{SC} and R_t^D mechanically, using the rule

$$R_t^{SC} = \frac{23}{29}R_{t,t+1} + \frac{6}{29}R_{t,t+30} - \rho^{SC}, \tag{9}$$

$$R_t^D = \frac{30-\tau}{29}R_{t,t+1} + \frac{\tau-1}{29}R_{t,t+30} + \tau\rho^D + (\tau-1)\rho^O, \tag{10}$$

where ρ^{SC} is the penalty margin on settlement cash,[14] ρ^D is the discount margin on discounting Reserve Bank bills, ρ^O is the additional cost of repurchasing the discounted Reserve Bank bills the following day,[15] and τ is the average maturity of the Reserve Bank bills discounted.[16]

Substituting (8), (9), and (10) into (6), we get

$$F(-Nd_t^* - S^*) = \frac{\frac{6}{29}(R_t - R_{t,t+30}) + \rho^{SC}}{\frac{7-\tau}{29}(R_t - R_{t,t+30}) + \tau\rho^D + (\tau-1)\rho^O + \rho^{SC}}.$$

Provided the RBNZ keeps policy instruments constant at levels satisfying

$$F(-S^*) = \frac{\rho^{SC}}{\tau\rho^D + (\tau-1)\rho^O + \rho^{SC}}, \tag{11}$$

the equilibrium $d_t^* = 0$ holds whenever $R_t = R_{t,t+30}$. This suggests that, despite the level of interest rates varying substantially over time, a bank has no incentive to borrow in the inter-bank market to hold additional settlement cash or lend in the inter-bank market to reduce its holdings of settlement cash. In this sense, the condition (11) pins down the combinations of settlement cash target (S^*), the distribution of forecast errors (F), the value of τ and the discount and penalty margins, ρ^D and ρ^{SC}, which are consistent with market-implemented monetary policy. Provided the central bank sets these parameters

[14]The rate paid on a bank's settlement cash holdings is currently 300 basis points below the seven-day cash rate. The seven-day rate is calculated as a simple weighted average of the market one-day and thirty-day rates. The 300 basis point penalty margin on settlement cash has not been used to alter interest rates in practice. The only change in margins during our study period took place when the penalty margin on settlement cash was changed for technical reasons on December 18th, 1991 (we explain such technical changes below).

[15]Whenever Reserve Bank bills are discounted, they are offered back to the market the following day.

[16]Reserve Bank bills (bills of 63 days maturity, issued by the RBNZ in twice-weekly tenders each of 70 million dollars) can be discounted back to the RBNZ for settlement cash if they have 28 or fewer days remaining to maturity. However, Reserve Bank bills are discounted at a rate above the market yield for equivalent maturity short-term securities (calculated as a weighted average of the one-day and thirty-day market rates). The difference between the discount rate and the market rate, called the discount margin and currently equal to 90 basis points, applies to the entire term of the bill discounted. Discounting is thus an expensive way for banks to raise settlement cash. The discount margin is seldom changed. Each of the four changes in the nearly nine year period we study corresponds to a simultaneous change in the target for settlement cash balances.

correctly, it can hold them constant over time.[17] Unlike the simple mechanism described above, the New Zealand mechanism to ensure money market equilibrium requires the yield curve to be flat at the very short end of the curve. In Appendix C we show that this is not needed, provided there are some small transaction costs in lending or borrowing in the inter-bank market.

Any change in the demand for money by households is automatically met with a change in the supply of money, through open market operations offsetting flows between households and banks. The monetary base, currency plus settlement cash, will therefore equal

$$P_t Y_t e^{-\theta R_t} + S^*.$$

Apart from the additional constant term S^*, this is identical to the monetary base in the simple mechanism discussed above. This implies that, provided the settlement cash target S^* is small relative to households' currency holdings, as it is in New Zealand, the implied growth rate of the monetary base is (approximately) the same as before. For the macro model we used previously, this is given by equation (19) in Appendix A.

With such a mechanism in place, together with a credible threat, it is possible for the central bank to oversee large changes in interest rates without resorting to formal policy changes. Figure 1 displays the nominal three-month interest rate in New Zealand (measured as the quarterly average) and the underlying inflation rate[18] (measured as an annual percentage change) from March 1989 to September 1997. Despite the lack of formal policy changes there was a period of mostly falling interest rates from early 1991 to early 1994, a subsequent period of interest rate firming till mid-1996 and a reversal with falling interest rates till the end of our sample in 1997.

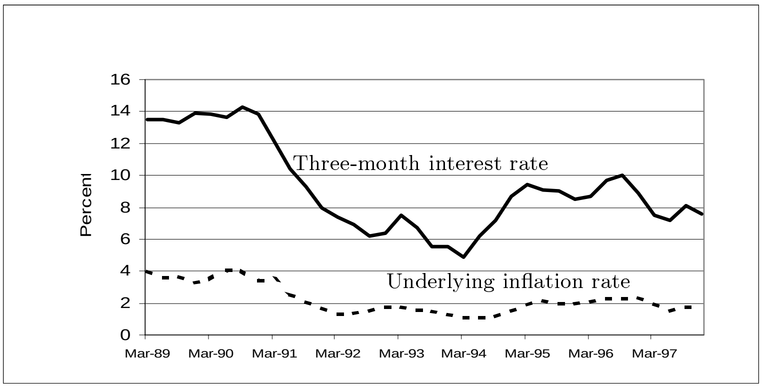
3 Open Mouth Operations

We have shown above that if the central bank makes a credible threat to launch immediate open market operations, markets will deliver the T-day interest rate equal to the central bank's preferred level. In proving this result we assumed that the process generating the central bank's preferred level of the interest rate was public knowledge. We now relax this assumption by allowing the possibility that this process is not entirely public knowledge.

[17] With a positive rate of inflation and output growth, (8) implies the monetary authorities forecasting effort must be continually improving. In the case of inflation, this lowers the real demand for settlement cash to match the decline in real settlement balances (S^*/P_t). Because this improvement in forecasting may not be possible beyond some point, the Bank may be forced periodically to adjust some or all of its policy instrument in a one-off measure to lower the level of accuracy required in its forecasts, and thus allow the nominal distribution of forecast errors to remain constant. These one-off changes have the interpretation of technical adjustments in policy instruments. They imply no change in the stance of monetary policy. This is consistent with the commentary surrounding the two technical changes which occurred during our sample period.

[18] The measured underlying inflation rate is the measure of inflation that the RBNZ was targeting over this period. Unlike New Zealand's headline consumer price inflation rate, it excludes mortgage interest charges.

Figure 1: The three-month interest rate and inflation (January 1989 – December 1997)



More precisely, we assume that the central bank's preferred level of the T-day rate at time t is

$$\hat{r}_{t,t+T} = \eta_t + \xi_t,$$

where the realization of η_t is public knowledge at time t and the realization of ξ_t is known only to the central bank. ξ_t can be thought of as private information of shocks to inflation or inflation pressures. Another interpretation is that ξ_t represents the outcome of central bank forecasting and modeling efforts, and hence the central bank's private view of the appropriate monetary conditions. Unless the central bank releases this to the public, it remains as private information.

We have argued that the private sector will deliver a T-day rate equal to its prediction of the central bank's preferred level. That is, the market T-day rate at time t will equal

$$r_{t,t+T} = E_t^{PS}[\hat{r}_{t,t+T}] = \eta_t + E_t^{PS}[\xi_t] = \hat{r}_{t,t+T} + (E_t^{PS}[\xi_t] - \xi_t).$$

where E_t^{PS} denotes expectations conditional on the private sector's information at time t. This will only equal the central bank's actual preferred level if $E_t^{PS}[\xi_t] = \xi_t$. The simplest way to ensure its goal is met is for the central bank to announce the value of $\hat{r}_{t,t+T}$ (or ξ_t) at all times t. If this model is correct, we would expect to see a continual stream of central bank announcements. However, we observe central bank announcements at discrete, unpredictable intervals. We can explain this phenomenon if central bank announcements are costly.

Suppose private sector and central bank views regarding appropriate monetary conditions differ. If the central bank announces its view, either through a statement or a formal policy change, and this view is subsequently found to be inferior to the private sector's, the reputation of the central bank will suffer. This risk of damaging its reputation discourages the central bank from making announcements. It is one motivation for our assumption that each time the central bank makes an announcement it incurs a small cost c. The magnitude of the cost is independent of the content of the announcement. We assume the central bank has a flow cost function $(r_{t,t+T} - \hat{r}_{t,t+T})^2$; when the T-day rate deviates from its target, expected inflation will deviate from its preferred level and the central bank's inflation objective will not be met. Large deviations in T-day rates (and in expected inflation rates) are disproportionately more costly than small deviations, motivating our choice of a quadratic cost function. We continue to suppose the central bank's threat is credible. That is, we suppose markets believe the central bank will carry out its threat to launch open market operations as soon as $r_{t,t+T} \neq E_t^{PS}[\hat{r}_{t,t+T}]$. The market will respond by delivering the T-day rate $E_t^{PS}[\hat{r}_{t,t+T}]$ at all times t. In this case, the flow cost at time t is

$$(r_{t,t+T} - \hat{r}_{t,t+T})^2 = (E_t^{PS}[\xi_t] - \xi_t)^2.$$

The central bank therefore chooses the timing of its announcements, and the information released, in order to minimize its total cost[19]

$$E\left[\int_0^\infty e^{-\kappa t}(E_t^{PS}[\xi_t] - \xi_t)^2 dt + \text{PV(announcement costs)}\right].$$

where κ is the rate at which future flow costs are discounted and PV represents the present value of announcement costs.

Because of the lump-sum nature of announcement costs, the central bank will not bother correcting small deviations between the market T-day rate and its preferred level. Instead, the central bank will wait until the deviation reaches a critically large level before releasing any private information. Since the cost incurred does not depend on the actual information released, the central bank will maximize the benefit it receives from making the announcement by releasing all its private information, resetting the prediction error $E_t^{PS}[\xi_t] - \xi_t$ to zero.

Suppose, for instance, that the central bank's private information follows a Brownian motion without drift:

$$d\xi_t = \sigma dz_t,$$

where dz_t is the increment of a standard Wiener process. Then the prediction error also follows a Brownian motion without drift:

$$d(E_t^{PS}[\xi_t] - \xi_t) = -\sigma dz_t.$$

However, by making an announcement the central bank can reset $E_t^{PS}[\xi_t] - \xi_t$ to any level it chooses. This is an example of a two-sided (S, s) model, as introduced by Scarf (1960). Because, in the absence of central bank announcements, the distribution of the prediction error is symmetric about zero, the optimal announcement policy is to reset the prediction error to zero whenever it moves outside a symmetric band about zero. More precisely, the instant $E_t^{PS}[\xi_t] - \xi_t$ moves outside the interval $[-\Delta^*, \Delta^*]$, the central bank should reveal all its private information. Notice that this condition is satisfied precisely when the market delivers a T-day rate which deviates from the target level by Δ^*. Dixit (1991) has shown that the optimal band is defined implicitly by

$$0 = \frac{\alpha\kappa}{2\Delta^*}\left(c - \frac{(\Delta^*)^2}{2\kappa}\right) + \frac{e^{\alpha\Delta^*} + e^{-\alpha\Delta^*} - 2}{e^{\alpha\Delta^*} - e^{-\alpha\Delta^*}},$$

[19] For mathematical convience we switch to using a continuous time specification in this section.

where $\alpha = \sqrt{2\kappa}/\sigma$. Since we have assumed announcement costs are small relative to the flow costs of interest rate deviations, we can use Dixit's approximation $\Delta^* \approx (2c\sigma^2)^{1/4}$. Note that the width of the band of acceptable levels of the T-day rate is an increasing function of both the cost of making an announcement and the volatility of the central bank's private information. If the current prediction error is $E_t^{PS}[\xi_t] - \xi_t$, the expected time until the next announcement is approximately

$$\frac{\sqrt{6c}}{\sigma} - \frac{(E_t^{PS}[\xi_t] - \xi_t)^2}{\sigma^2},$$

as shown by Dixit (1993, Section 6.1). On average, the time between announcements is $\sqrt{6c}/\sigma$. If announcement costs are high, central bank announcements will be relatively rare; if the central bank's private information is highly volatile, announcements will be frequent.

We have argued that market rates incorporate all publicly available information when central bank action is threatened. Since central bank anouncements release new information, each announcement should lead to a discrete jump in the level of interest rates. The changes in market rates should not be predictable using publicly available information — if the released information could be anticipated, there would be no need for the central bank to make a costly announcement. We test this implication in Section 5.

Our model of open mouth operations also suggests that the more volatile is the central bank's private information, the more announcements are necessary. To minimize the need for such announcements, which we consider to be costly, the central bank should be as transparent as possible. In New Zealand, the RBNZ achieves this through the use of an explicit monetary conditions index, as well as the detailed and timely releases of inflation projections and the assumptions underlying these projections. Despite the RBNZ's transparent approach, open mouth operations are sometimes needed. A normal response is an official comment from a senior Bank official or the Governor, broadcast to the financial markets over the electronic wire services, or a formal news release by the Governor. In the past, the RBNZ has used the structure of open market operations, as well as statements, to signal the strength of its views. Typically, this involved a decision not to resell discounted Reserve Bank bills to the market, a decision to reject some bids for treasury bills offered to the market, or to inject funds only by purchasing a security outright rather than through repurchase arrangements. However, the liquidity impact of such moves was negligible. In the words of the Reserve Bank (Huxford and Reddell, 1996), "Typically, it was not the direct financial impact of the decision concerned that mattered, but rather the implied signal of central bank disquiet." The use of such formal signalling was discontinued by 1995.[20] We will study the impact of statements with and without the use of formal signalling.

[20] As Borio (1997) points out, such signalling is still frequently used by central banks in other countries.

4 Data

Our sample period is January 1st, 1989 through September 30th, 1997. We chose to start our sample in 1989 since this is the year the Reserve Bank Act was introduced, under which the Bank was mandated to target "price stability." The methods of implementing monetary policy evolved throughout the late 1980s and early 1990s, so in this sense the start date is somewhat arbitary. All financial data was obtained from the RBNZ. For short maturities we used bank bill rates rather than T-bill rates, since we could not obtain daily data on T-bill rates until February 1997. There are three reasons why we think this is not a problem. Firstly, these are the rates the RBNZ refers to in its statements. Furthermore, the market for bank bills is much more liquid than the market for T-bills. Finally, bank bill rates command a premium of around 20 basis points over T-bill rates and this low premium is quite stable over time, reflecting the consistently high credit rating of the banks that issue these bills.[21] Bank bills are discount instruments which pay no coupon. For the whole sample, we obtained the overnight cash rate ($R1D$), the one-month bank bill rate ($R1M$), the three-month bank bill rate ($R3M$), the five-year government bond yield ($R5Y$) and the trade-weighted index (TWI), which measures the foreign value of the New Zealand dollar based on a basket of New Zealand's five largest trading partners. We define the monetary conditions index to be $MCI = R3M + 50\ln(TWI)$, based on the RBNZ's rule that a two percent appreciation in TWI is equivalent to a 100 basis point increase in $R3M$. There were 2149 observations left on each variable after deleting missing observations for weekends and holidays. All rates are measured daily at 11am.[22] Daily settlement cash forecast errors of the RBNZ, denoted FE, were also obtained from the RBNZ for the same period.

To construct the dummy variable $ANNOUNCE$ for open mouth operations, we obtained all articles from Reuters which contained the words "Reserve Bank" and either "Monetary" or "Brash."[23] We used several alternative search strings, including the names of other RBNZ officials, to cross-check these were appropriate search items. Using these we were only able to identify a few additional statements which we in turn added. In addition, the articles were cross-checked with the chronology of events contained within the three major RBNZ publications — *Monetary Policy Statement*, *Economic Projections* and *Reserve Bank Bulletin*. No new articles were found from these sources. Using all the articles found we deleted articles which did not contain references to monetary conditions, or where the comments made were judged to be neutral or ambiguous with regard to monetary conditions, or where formal policy instruments were changed (for example, changing the settlement cash target). The remaining articles were trimmed to highlight the relevant RBNZ statements. These observations are coded $STATEMENT = 1$, as

[21]For instance, using available 1997 daily data, the average premium on $R1M$ is 21.75 basis points (with a standard deviation of 1.82 basis points) and on $R3M$ is 21.80 basis points (with a standard deviation of 2.28 basis points).

[22]We also obtained hourly data for $R1D$, $R1M$, $R3M$, $R5Y$, and TWI, from August 22nd, 1996 to September 30th, 1997.

[23]Donald Brash was the governor of the RBNZ throughout the period. A large number of the statements were made by him.

opposed to all other observations which are coded $STATEMENT = 0$.[24]

Each statement is then coded according to the dummy variables $TIGHTEN$, $SIGNAL$ and $SURPRISE$. These are defined as zero except as follows:

- $TIGHTEN = 1$ if the statement suggests a desire of the RBNZ to have tighter monetary conditions. $TIGHTEN = -1$ if the statement suggests a desire of the RBNZ to have looser monetary conditions.
- $SIGNAL = 1$ if the statement is accompanied by a formal signal from the Reserve Bank (a change in the structure of that day's open market operation as described in Section 3).
- $SURPRISE = 1$ if the statement is a surprise statement, as opposed to part of a formal release of information, such as *Monetary Policy Statement* or *Economic Projections*. These appear at three-monthly intervals at dates which are known in advance and are coded as $SURPRISE = -1$. The remaining statements are from speeches, the dates of which are known in advance, and are coded $SURPRISE = 0$.

For most of our empirical work we are interested only in the impact of surprise statements. We therefore define

$$ANNOUNCE = \begin{cases} 1 & \text{if } STATEMENT = 1,\ TIGHTEN = 1 \\ & \quad \text{and } SURPRISE = 1, \\ -1 & \text{if } STATEMENT = 1,\ TIGHTEN = -1 \\ & \quad \text{and } SURPRISE = 1, \\ 0 & \text{otherwise.} \end{cases}$$

We use the dummy variable $A = ANNOUNCE$ as our standard measure of open mouth operations, referring to $A = 1$ as a tightening announcement and $A = -1$ as a loosening announcement.

Statements were made on 106 days during our sample period. Of these, 66 statements indicated a need for tighter monetary conditions and 40 for looser conditions, 64 were genuine surprise statements ($SURPRISE = 1$), 18 were speeches ($SURPRISE = 0$) and the remaining 24 were part of regular information releases ($SURPRISE = -1$). In total, 15 announcements were accompanied by signals, with 13 of these being surprise announcements. The $ANNOUNCE$ variable took the value 1 on 37 days and -1 on 27 days.

5 Empirical Investigation of Open Mouth Operations

In this section, we explore whether open mouth operations are predictable, as well as their implications for interest rates and exchange rates.

[24] These articles, the authors' codification and all financial data are available from the authors upon request.

5.1 Are Open Mouth Operations Predictable?

An important implication of our theory is that an open mouth operation represents a surprise to the private sector. If the market already knows that the RBNZ wants a change in monetary conditions, the market will already have delivered it. We test this implication by seeing whether tightening and loosening announcements are predictable. To do this we employ an ordered probit model, using lagged information on announcements and financial variables to try to best predict open mouth operations:

$$A_t = \begin{cases} -1 & \text{if } b(L)X_{t-1} + c(L)A_{t-1} + \xi_t < a_1, \\ 0 & \text{if } a_1 < b(L)X_{t-1} + c(L)A_{t-1} + \xi_t < a_2, \\ 1 & \text{if } a_2 < b(L)X_{t-1} + c(L)A_{t-1} + \xi_t, \end{cases}$$

where X_{t-1} represents a lagged interest rate, exchange rate or settlement cash forecast error, ξ_t is normally distributed and $b(L)$ and $c(L)$ are polynomials in the lag operator:

$$b(L) = \sum_{j=0}^{m} b_j L^j, \quad c(L) = \sum_{j=0}^{n} c_j L^j.$$

We estimate the model by maximum likelihood and conduct a Wald test that the coefficients on the lagged variables are jointly insignificant ($\text{H}_0 : b_0 = 0, \ldots, b_m = 0, c_0 = 0, \ldots, c_n = 0$). We also calculate the change in estimated probability of an announcement following various events.

The number of lags m and n is chosen by optimizing over all possible lag lengths (with up to ten lags) using the Schwarz Bayesian Information Criterion. We consider seven different models, each corresponding to a different measure of X_{t-1}. In all seven cases, optimizing this criterion implies including no lags in the model. In itself, this is suggestive that lagged variables do not help predict announcements. To formally test this we consider the case that one lag of each variable is included in the model. Table 1 presents the results. Only in the models which include the exchange rate (the fifth and sixth rows of Table 1) is past information significant at the 5% level in predicting announcements.[25]

From the estimated likelihood function, we calculate the change in probability of a tightening announcement following a tightening announcement the previous day, $\Pr[A_t = 1|A_{t-1} = 1] - \Pr[A_t = 1|A_{t-1} = 0]$, which we denote $\Delta \Pr |(A_{t-1} = 1)$. We also calculate the change in probability of a tightening announcement following a 25 basis point rise in an interest rate, exchange rate or the monetary conditions index the previous day, or a 25 million dollar RBNZ settlement cash forecast error the previous day. We denote this $\Delta \Pr |(X_{t-1} = 25)$. In calculating these probability changes we take the mean probability change over all observations. In each case, the impact on the probability of announcements today is negligible. A tightening announcement yesterday lowers the estimated probability of a tightening announcement today by slightly over half of one percent. Similarly, a 25

[25]There is some evidence that over time markets learnt of this correlation between exchange rates and future announcements, thus eliminating it. We repeated the above test of predictability for the second half of the sample (p-values are 0.3844, 0.4492, 0.4303, 0.3081, 0.1717, 0.1889 and 0.2696 for the models with $R1D$, $R1M$, $R3M$, $R5Y$, TWI, MCI and FE respectively).

Table 1: Predictability of Announcements (A_t)

(X_{t-1}, A_{t-1})	p-value from test $b_0 = c_0 = 0$	$\Delta \Pr \vert (A_{t-1} = 1)$	$\Delta \Pr \vert (X_{t-1} = 25)$
$(\Delta R1D_{t-1}, A_{t-1})$	0.8107	−0.0057	0.0002
$(\Delta R1M_{t-1}, A_{t-1})$	0.8270	−0.0059	−0.0001
$(\Delta R3M_{t-1}, A_{t-1})$	0.8259	−0.0059	−0.0003
$(\Delta R5Y_{t-1}, A_{t-1})$	0.8266	−0.0059	−0.0003
$(\Delta TWI_{t-1}, A_{t-1})$	0.0420	−0.0061	−0.0047
$(\Delta MCI_{t-1}, A_{t-1})$	0.0452	−0.0066	−0.0050
(FE_{t-1}, A_{t-1})	0.7573	−0.0059	−0.0009

basis point rise in any of the financial rates lowers the estimated probability of a tightening announcement today by no more than half of one percent. Even though there is some evidence of statistical predictability of announcements when lagged exchange rates are included (at least in the earlier part of the sample), it is clear from these experiments that the magnitude of this effect is negligible.

5.2 The Impact of Open Mouth Operations

In what follows we study the dynamic response of interest rates, exchange rates and the daily settlement cash forecast error of the RBNZ, following open mouth operations. We use a structural VAR approach, taking announcements as exogenous shocks. Our structural model has the following form:

$$\begin{aligned} \Delta X_t &= \alpha + \alpha_X(L)\Delta X_{t-1} + \alpha_{FE}(L)FE_t + \alpha_A(L)A_t + \alpha_D\,\bar{D}_t + u_{1t} \\ FE_t &= \beta + \beta_X(L)\Delta X_{t-1} + \beta_{FE}(L)FE_{t-1} + \beta_A(L)A_t + \beta_D\,\bar{D}_t + u_{2t} \end{aligned} \tag{12}$$

where

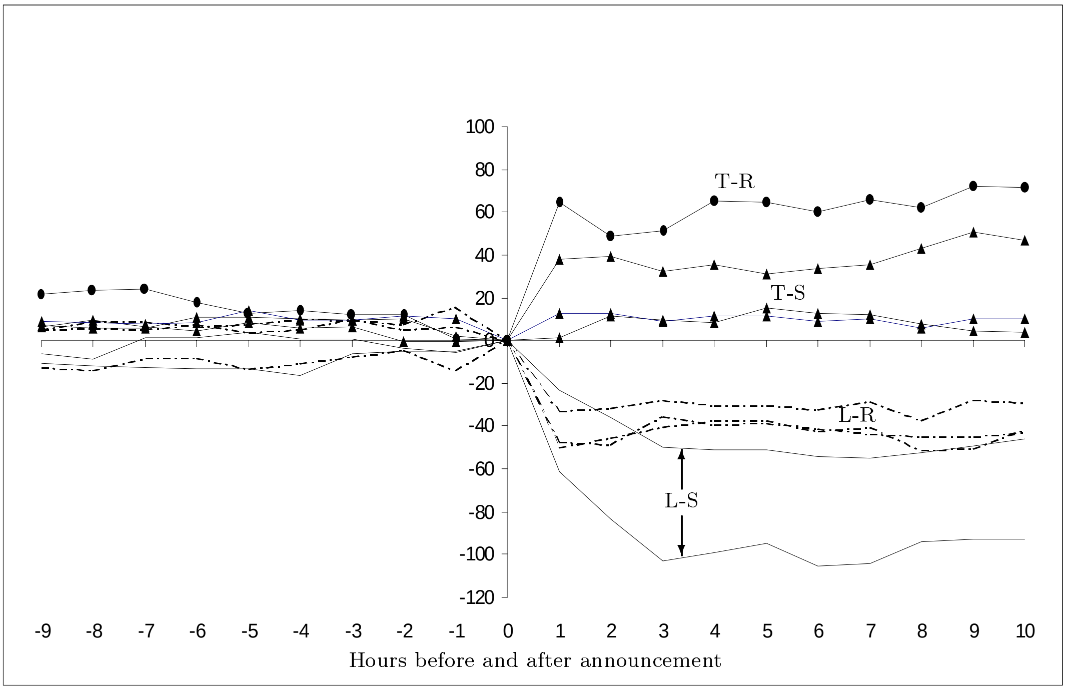
$$\begin{pmatrix} u_{1t} \\ u_{2t} \end{pmatrix} \sim N\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_{11} & 0 \\ 0 & \sigma_{22} \end{pmatrix}\right],$$

$$\alpha_y(L) = \sum_{j=0}^{p_y} \alpha_{y,j}L^j, \quad \beta_y(L) = \sum_{j=0}^{q_y} \beta_{y,j}L^j, \quad \text{for } y \in \{X, FE, A\},$$

L^j is the standard lag operator, X_t is an interest rate or exchange rate, FE_t is the RBNZ settlement cash forecast error, A_t is our measure of announcements and $\bar{D}_t$ is a vector of dummy variables for the days of the week as well as the day before and the day after each public holiday. Two types of identifying assumptions are made in (12).

Firstly, announcements do not depend on lagged or contemporaneous values of interest rates, exchange rates or the RBNZ forecast error. This is consistent with our theory of open mouth operations. An alternative theory, in which announcements depend on current or lagged monetary conditions, is that when monetary conditions loosen the RBNZ releases a tightening statement. We have already shown in the previous section that announcements do not depend in an important way on lagged financial data. A sudden

Figure 2: The Monetary Conditions Index (MCI) before and after each announcement (normalized to zero just before each announcement and expressed in basis points)



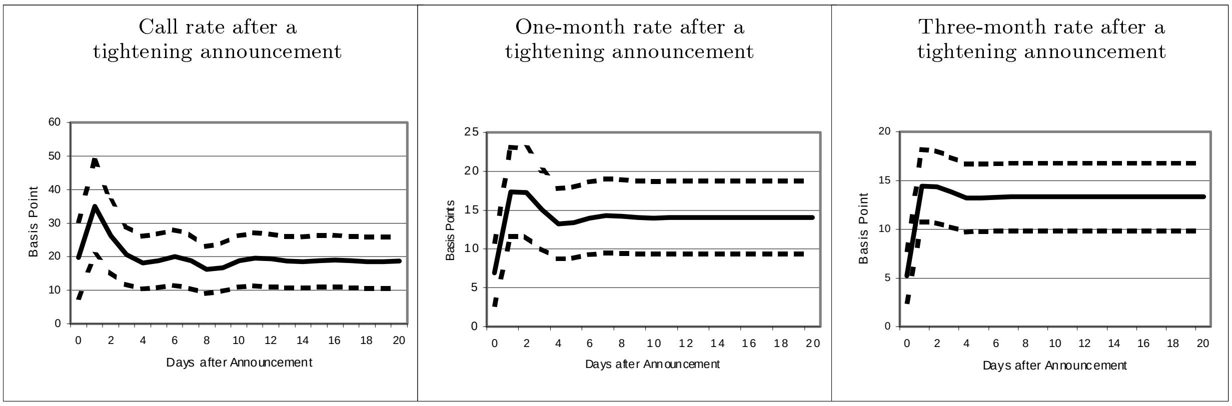
T = tightening, L = loosening, S = surprise announcement, R = statement made at three-monthly release. The nine announcements represent all announcements made during 8/22/96–9/30/97.

loosening of monetary conditions, however, might lead to a tightening statement within the same day. In this case we would expect a tightening announcement to be contemporaneously correlated with a fall in the interest rate. This is not what we find. Additional support for our identifying assumption arises from using hourly data. From August 22nd, 1996 to September 30th, 1997 we have hourly data on interest rates and exchange rates. Figure 2 shows the monetary conditions index before and after each statement, for all nine statements in this period (there were five surprise announcements ($SURPRISE = 1$), as well as four statements made as part of the regular three-monthly releases of information ($SURPRISE = -1$)). Up until the time of each statement there is no obvious movement in monetary conditions. However, immediately following each statement, the monetary conditions index moves in the direction predicted by our theory.[26]

The second assumption is that the daily settlement cash forecast error does not depend on contemporaneous changes in interest rates or exchange rates, although it can depend on lagged interest rates or exchange rates. Forecasts are made using past information. The actual realization of the forecast error will depend on current net flows between the government and the private sector. It seems unlikely that the same day's interest rate or exchange rate could alter the size of these flows which are determined in advance. In

[26]The responses of individual interest rates and the TWI exchange rate exhibit similar behavior.

Figure 3: Effects of a tightening announcement



any case, this assumption turns out not to matter in the sense that reversing this timing assumption does not materially alter the estimated announcement effects.

For each interest rate and exchange rate series ΔX_t, optimal lag lengths are chosen for $\alpha_X(L)$ and $\beta_X(L)$, together with the optimal lag lengths for $\alpha_{FE}(L)$, $\alpha_A(L)$, $\beta_{FE}(L)$ and $\beta_A(L)$, with a maximum of ten lags on each variable considered. The Schwarz Bayesian Information Criterion is used. We consider three different sample periods as well as two different definitions of announcements, as detailed below. Thus, for each equation we estimate six different regressions. For each of these, we consider one thousand different lag length permutations to choose the optimal lag lengths in the VAR. We find optimal lag structures are one lag of each variable for all equations estimated, except the equation for $\Delta R1D_t$ (which requires at most eight lags of $\Delta R1D_t$), the equation for $\Delta R1M_t$ (which requires at most ten lags of $\Delta R1M_t$), and the equation for $\Delta R3M_t$ (which requires at most three lags of $\Delta R3M_t$). The reduced form models are estimated using the SUR estimator, and a Choleski decomposition is used to recover the structural parameters. The dynamic impact of announcements and shocks to the forecast error is then calculated from the estimated structural model.

Figure 3 contains the impulse response functions of the one-day rate, the one-month rate, and the three-month rate to a surprise tightening announcement, using the whole sample period, and with 95% approximate confidence intervals calculated using a Monte Carlo simulation with 1000 draws. A typical surprise tightening announcement leads to a 37 basis point jump in the one-day rate, an 18 basis point jump in the one-month rate, and a 14 basis point jump in the three-month rate, all after one day. Interest rates are measured at 11am, while announcements are made throughout the day, so the correct measure of the contemporaneous impact of announcements is the impact after one day. After three further days, the total impact is around 20 basis points on the one-day rate, 15 basis points on the one-month rate, and around 13 basis points on the three-month rate. All three rates remain around these levels in subsequent days. The decline in these interest rates from day one to day four is the result of negative autocorrelation in the interest rate series,

Table 2: Reaction of Financial Variables to Announcements

Sample period:	1/1/89–9/30/97		1/1/89–6/22/93		6/23/93–9/30/97	
Statements where:	Surprise	All	Surprise	All	Surprise	All
$\Delta R1D_t$	36.66	27.11	46.13	36.82	21.01	16.19
	(6.08)	(4.69)	(10.21)	(8.50)	(5.95)	(4.41)
$\Delta R1M_t$	17.97	14.80	18.17	15.88	16.79	13.80
	(2.80)	(2.11)	(4.18)	(3.12)	(3.68)	(2.70)
$\Delta R3M_t$	14.38	11.77	13.48	10.89	15.12	12.24
	(1.88)	(1.47)	(2.44)	(2.05)	(3.07)	(2.20)
$\Delta R5Y_t$	4.20	3.76	3.24	3.25	5.67	4.41
	(1.33)	(1.04)	(1.61)	(1.32)	(2.19)	(1.62)
ΔTWI_t	5.60	8.59	8.41	7.68	2.25	9.83
	(3.80)	(2.97)	(5.48)	(4.34)	(5.54)	(4.17)
ΔMCI_t	18.82	18.70	20.45	17.59	16.56	19.93
	(3.49)	(2.67)	(5.43)	(4.36)	(4.31)	(3.07)
FE_t	-0.46	-2.61	4.89	0.11	-7.77	-4.89
	(3.06)	(2.70)	(4.27)	(3.51)	(4.71)	(3.37)
FE_{t+1}	-0.55	-1.65	0.38	-2.29	-2.92	-0.81
	(3.08)	(2.54)	(4.30)	(3.54)	(4.60)	(3.37)
FE_{t+20}	2.2E-4	1.6E-4	-6.1E-4	-6.5E-4	-0.004	-0.003
	(2.3E-3)	(1.2E-3)	(3.7E-3)	(3.5E-3)	(0.007)	(0.005)

Note: Approximate standard errors are in parenthesis. Calculated using a Monte Carlo simulation with 1000 draws. The impact of announcements on forecast errors is found using the model estimated with $\Delta R1D_t$.

captured in the estimated model. For the five-year bond rate, the exchange rate and the monetary conditions index, because of the simpler lag structure (one lag of each variable), the impulse response is essentially flat after day one. Table 2 reports the results for all six rates, using two definitions of announcements (only surprise statements, as well as all types of statements), for three different sample periods (whole sample, first half of sample, and second half of sample). The results show that announcement effects are broadly consistent over different sample periods, interest rate maturities and announcement types. For brevity, Table 2 reports only the impact on rates one day after the announcement is made.[27]

How can we explain large jumps in interest rates and exchange rates immediately following a RBNZ announcement? A conventional explanation would be that tightening announcements contain new information implying higher current or future inflation, and

[27] We also checked Table 2 for sensitivity to outliers. For each variable, we capped observations that were more than three standard deviations away from their mean. Overall, the magnitude of the announcement effects dropped slightly, although the statistical significance of the results was slightly enhanced.

thus a revision upwards by the market in nominal interest rates.[28] In this case, the New Zealand dollar should depreciate with the announcement. Another interpretation of announcements is that they signal a change in the preferences of the central bank, a tightening implying the central bank wants to get tough on inflation. In this case, long-term interest rates should fall as future inflation is now expected to be lower.

We find neither of these results. According to our theory of open mouth operations, announcements play quite a different role. The RBNZ's inflation target ties down fairly precisely the RBNZ's preferences over future inflation as well as long-term inflation outcomes. Instead, announcements reveal the RBNZ's interpretation of the monetary conditions that are needed to keep future inflation on target. In this case tightening announcements raise both short-term and long-term interest rates and cause the exchange rate to appreciate. Consistent with this we find interest rates of all maturities increase significantly following a tightening announcement, together with some appreciation of the exchange rate.[29] In the remainder of this section we rule out other explanations for our findings.

Another potential explanation for the announcement effects found above is that announcements occur simultaneously with changes in open market operations, and it is these open market operations which cause interest rates to change. It is true, that to the extent announcements change interest rates, these changes will lead to an endogenous change in open market operations. However, what we wish to show is that changes in open market operations are not responsible for the changes in interest rates we observe after announcements. Given that the RBNZ holds its settlement cash target constant and that open market operations are conducted with the aim of leaving the system with the target level of aggregate settlement cash balances each day, the only way for the RBNZ to use open market operations to manipulate interest rates is to make intentional "forecast errors." Each day the RBNZ makes forecasts of the net flow of funds between the government and the private sector and, based on these forecasts, conducts open market operations to offset the projected impact flows have on end of day settlement cash. By incurring a positive forecast error, the RBNZ can effectively inject cash into the settlement process without changing its settlement cash target. The last three rows of Table 2 report the impact of a tightening announcement on the forecast error for the same day as the announcement, for the cumulative forecast error after one further day and the cumulative forecast error after twenty days. On the day of the announcement, the forecast error varies between -7.77 million dollars and 4.89 million dollars, depending on the sample period and the definition of announcements used. A 95% confidence interval suggests that this forecast error is considerably less than 20 million dollars. In no cases are the results statistically significant at the 5% level. One day after the announcement, the cumulative forecast error

[28]An immediate problem with this explanation is that in New Zealand all data pertinent to inflation is released to the public at the same time as it is released to the Bank.

[29]These announcement effects are consistent with those found by Engel and Frankel (1984) and others, who showed that under the period of money growth targeting in the United States, announcements of higher than expected money growth signalled future monetary tightening, thus raising real interest rates and appreciating the dollar. One difference between such announcement effects and open mouth operations, is that with the latter, even overnight interest rates change with the announcement, despite the fact policy settings are (and will remain) unchanged.

varies between -2.92 million dollars and 0.38 million dollars and is not significant, while after 20 days the cumulative forecast error is essentially zero.

To confirm that open market operations cannot be responsible for the announcement effects found above, we examine the impact of a 20 million dollar forecast error on the cash rate.[30] We use our hourly data to construct the daily change in the cash rate, measured at 8am. We cannot use our daily data for this purpose, since the cash rate is measured at 11am, while open market operations occur some time between 9am and 11am (so between 11am and 11am the next day we will be measuring the impact of two, potentially offsetting, open market operations). Using the model defined by equation (12) above, we find that on the day of a 20 million dollar positive forecast error (from 8am on the day to 8am the next day), the cash rate falls by 0.31 basis points (standard error is 0.13), and that by the next day the cash rate is unaffected (cumulative change is -0.04 basis points with a standard error of 0.64).[31] These results are consistent with what we know about the RBNZ's operating procedures: any forecast error is reversed the subsequent day. This very small daily liquidity effect implies that the channel from announcements to interest rates, through open market operations, can explain only a trivial part, if any, of the change in interest rates.

The final explanation we consider for our results is the use of formal signalling by the RBNZ. In the earlier part of the sample, the RBNZ occasionally used explicit signals when making announcements; that is, changes in the structure of open market operations for one day ($SIGNAL = 1$). We have three reasons for believing that these formal signals are not driving our results. Firstly, we re-estimated the model, dropping announcements which were accompanied by these signals. We find that the maximal announcement effect again occurs after one day. The cash rate rises by 17.96 basis points for surprise announcements and 15.88 basis points for all announcements (the standard errors are 7.08 and 5.41 respectively). The smaller increase in short-term interest rates, compared to Table 2, can be explained by the role formal signalling played earlier in the sample as a mechanism for clarifying the direction of statements and signifying a larger required change in rates. The important thing to note is that even dropping announcements with formal signals, announcements still have statistically and economically significant impacts on the cash rate (the results are similar for other rates). Secondly, results are presented for the second half of the sample, where there are no observations with $SIGNAL = 1$, in Table 2 above. This again shows the significance of our results does not depend on the inclusion of formal signals. Finally, the one day changes in open market operations are simply not large enough to explain the observed change in the cash rate based on a liquidity argument. According to our calculations, the average size of the change in open market operations,

[30] Hamilton (1997) models the Federal Reserve's forecasting errors caused by unanticipated flows between the U.S. Treasury and private sector banks, and uses these to estimate the liquidity effect in the U.S. Unlike Hamilton, we directly observe the equivalent forecasting errors for New Zealand.

[31] These results are based on using only surprise announcements, with the same lag length as used in Table 2 for the cash rate regression. The optimal lag length for the 8am interest rate series includes only one lag of the cash rate (not eight lags). Using only one lag for the cash rate gives results of -0.18 basis points on the day of the 20 million dollar forecast error (standard error is 0.12) and a cumulative change of 0.01 basis points one day after the 20 million dollar forecast error (standard error is 0.66).

corresponding to these signals, was less than 21 million dollars. From our point estimate of the liquidity effect, this changes the cash rate by a trivial 0.33 basis points for one day.

6 Conclusion

This paper presented a model in which investors, acting in self-interest, force interest rates to the levels desired by the monetary authority (market-implemented monetary policy). If interest rates move out of line with those required by the monetary authority, a statement (an open mouth operation) is all that is needed to restore them. Our model highlighted what we think are the most important requirements for a central bank to successfully replicate such a framework: paying market-based interest rates on reserves (settlement cash), linking the discount rate to market interest rates, ensuring transparency, and maintaining a high level of credibility. We also detailed the implementation of monetary policy in New Zealand, arguing it works in this way, and showing that it implies the monetary base is endogenous. A novel feature of the New Zealand approach is its reliance on the market to implement monetary policy, a factor which we believe serves to lower the political costs of a low-inflation policy and thus reduce any upward bias in inflation expectations.

In the empirical section of the paper, we explored the impact of open mouth operations. We found that following RBNZ tightening announcements, interest rates of all maturities increase and the New Zealand dollar appreciates. We showed that these changes are not caused by simultaneous changes in open market operations. We argued tightening announcements do not indicate a lowering in the RBNZ's inflation goal, or higher long-term inflationary outcomes. Instead, we argued that interest rates increase following tightening announcements predominantly because they signal that the RBNZ desires higher real interest rates compared to those delivered by the markets.

This finding has implications for understanding, and improving, the implementation of monetary policy in other countries. Most countries rely on announced changes in very short-term interest rate targets, such as the federal funds rate in the United States, to influence medium- and longer-term rates. The New Zealand approach allows the central bank to directly target the variable it cares most about. In the case of New Zealand this is now a combination of the three-month interest rate and the trade weighted exchange rate. Even within a traditional framework this raises an interesting question — could monetary authorities improve their implementation of monetary policy by making explicit announcements on rates other than the overnight interest rate?

Another possibility is that the use of open market operations in other countries to influence short-term interest rates could work in part through a similar mechanism to the one identified here. This view appears to be shared by a recent Bank of International Settlements survey on monetary policy implementation in fourteen countries (excluding New Zealand): (Borio, 1997, p. 43)

> "*Supplying, say, a somewhat larger amount [of reserves] than that targeted by banks is expected to put downward pressure on the overnight rate. It is still an open question, however, how much of the downward pressure occurs through a*

mechanical liquidity effect or, more fundamentally, through the signal conveyed regarding policy intentions."

and (Borio, 1997, p. 89)

"*But how can mere announcements have such a critical effect? That they clearly do is evident from the fact that in some cases policy signals are sent, and market rates change, without any liquidity operations ever taking place... [T]he answer perhaps lies in the fact that as monopolist supplier of settlement balances, the central bank could, if it so wanted, set the overnight rate. It could do so by injecting/withdrawing the volume of settlement balances demanded by the market at the desired rate. And, through arbitrage, it could influence rates further along the money market yield curve for the period in which no further change was anticipated.*"

Statements such as these suggest that the experience of New Zealand may not be so removed from that of other countries. To the extent announcements in other countries play the same role that open mouth operations play in New Zealand, these announcements could help explain the small liquidity effects found in practice, despite the apparent ease with which overnight rates, as well as other rates, move substantial amounts when changes are desired by monetary authorities. With this in mind, future research should examine the extent to which announcements and signals, rather than open market operations, initiate interest rate movements in countries other than New Zealand. Regardless of the operating procedures of different central banks, we believe signalling monetary policy intentions lies at the heart of monetary policy implementation. In this regard, the experience of New Zealand may provide valuable lessons for central bankers in other countries.

Appendices

A A Simple Macro Model

The following is a modified version of a macro model which has been used widely in the macroeconomics literature. It is most similar to the flexible price version of the model in Kerr and King (1996). Where possible we have used the same notation. The only significant modification to their model is to allow aggregate demand to depend on a longer-term interest rate (the T-day rate), rather than the standard assumption of the overnight interest rate. This motivates why the central bank's reaction function is written in terms of the T-day rate, rather than the overnight interest rate. Money demand still depends on the overnight interest rate.

All parameters are defined to be positive. We define inflation as $\pi_t = p_t - p_{t-1}$, where p_t is the log of the price level. We assume a flexible-price aggregate supply relationship

$$\pi_t = E_{t-1}\pi_t + \psi(y_t - y_t^*), \tag{13}$$

where y_t is the log of output. Potential output y_t^* is modeled as a random walk with drift, so that in logarithmic form $y_t^* = y_{t-1}^* + \delta + \mu_t^y$ where $E_{t-1}\mu_t^y = 0$.[32] If $E_{t-1}\pi_t$ is removed from (13), a sticky-price version of the model is easily derived. Aggregate demand y_t depends positively on expected future output $E_t y_{t+1}$ and negatively on the T-day real interest rate $r_{t,t+T}$:

$$y_t = E_t y_{t+1} - \delta - s(r_{t,t+T} - r_{t,t+T}^*) + u_t.$$

The term u_t is an AR(1) demand shock, so that $u_t = \rho u_{t-1} + \zeta_t$, where $|\rho| < 1$ and $E_{t-1}\zeta_t = 0$. The equilibrium real interest rate $r_{t,t+T}^*$ is assumed to follow a random walk without drift, so that $r_{t,t+T}^* = r_{t-1,t-1+T}^* + \mu_t^r$, where $E_{t-1}\mu_t^r = 0$. The Fisher equation is used to describe the relationship between the T-day nominal and T-day real interest rates. That is,

$$R_{t,t+T} = r_{t,t+T} + E_t\pi_{t,t+T},$$

where the expected rate of inflation over the next T days is $E_t\pi_{t,t+T} = \frac{1}{T}E_t\sum_{k=1}^{T}\pi_{t+k}$. The monetary authority has the reaction function

$$R_{t,t+T} = r_{t,t+T}^* + \pi^* + g(\pi_t - \pi^*) + x_t,$$

where $E_{t-1}x_t = 0$ and π^* is its inflation target. We assume $g > 1$, as in Kerr and King (1996), which ensures a unique rational expectations equilibrium exists. The rational expectations solution to this set of equations is

$$\pi_t = \pi^* - \frac{\psi s}{1+\psi s g}x_t + \frac{\psi}{\lambda}u_t + \frac{\rho}{sg\lambda}u_{t-1}, \tag{14}$$

$$y_t = y_t^* + \frac{1}{\lambda}\zeta_t - \frac{s}{1+\psi s g}x_t, \tag{15}$$

$$r_{t,t+T} = r_{t,t+T}^* + \frac{1}{s}\left(\frac{s}{1+\psi s g}x_t + \left(1 - \frac{1}{\lambda}\right)u_t + \frac{\rho}{\lambda}u_{t-1}\right),$$

$$R_{t,t+T} = r_{t,t+T}^* + \pi^* + \frac{1}{1+\psi s g}x_t + \frac{\psi g}{\lambda}u_t + \frac{\rho}{s\lambda}u_{t-1},$$

where

$$\lambda = (1+\psi s g)\left(1 - \frac{\rho(1-\rho^T)}{gT(1-\rho)}\right) > 0.$$

We assume money market equilibrium requires

$$m_t = p_t + y_t - \theta R_t, \tag{16}$$

where m_t is the log of the monetary base and

$$R_t = r_{t,t+T}^* + \pi^* + \frac{T}{1+\psi s g}x_t + \frac{T(\psi s g(1-\rho) - (\rho - \rho^T))}{s\lambda(1-\rho^T)}u_t + \frac{\rho T}{s\lambda}u_{t-1} \tag{17}$$

is the overnight rate. Its construction is described in Section 2. When first differenced, (16) defines the growth rate of money as

$$\Delta m_t = \pi_t + \Delta y_t - \theta\Delta R_t. \tag{18}$$

[32]If a random variable is added to equation (13), we can easily derive the impact of supply shocks. This does not change the basic nature of the solutions below.

Substituting (14), (15), and (17) into (18) gives a rule for the growth rate of the monetary base consistent with the interest rate rule:

$$\begin{aligned} \Delta m_t &= \pi^* - \frac{\psi s}{1+\psi sg} x_t + \frac{\psi}{\lambda} u_t + \frac{\rho}{sg\lambda} u_{t-1} \\ &\quad + \delta + \mu_t^y + \frac{1}{\lambda}(\zeta_t - \zeta_{t-1}) - \frac{s}{1+\psi sg}(x_t - x_{t-1}) \\ &\quad - \theta \Bigg(\mu_t^r + \frac{T}{1+\psi sg}(x_t - x_{t-1}) \\ &\qquad + \frac{T(\psi sg(1-\rho) - (\rho - \rho^T))}{s\lambda(1-\rho^T)}(u_t - u_{t-1}) + \frac{\rho T}{s\lambda}(u_{t-1} - u_{t-2}) \Bigg) . \end{aligned} \tag{19}$$

The price level and the level of the monetary base are then uniquely determined at any point in time once the initial level of the monetary base (or initial level of prices) is specified.

B Proofs

B.1 Proof of Lemma 1

We first prove that if such a process for the overnight rate exists, it must be unique. If (2) is to hold, then

$$\hat{R}_t + T\sum_{i=0}^{N-1} E_t[\hat{R}_{t+1+iT,t+1+(i+1)T}] = T\sum_{i=0}^{N-1} E_t[\hat{R}_{t+iT,t+(i+1)T}] + E_t[\hat{R}_{t+NT,t+NT+1}]$$

must hold for all positive integers N. Therefore, the overnight rate must equal

$$\begin{aligned} \hat{R}_t &= E_t[\hat{R}_{t+NT,t+NT+1}] \\ &\quad + T\sum_{i=0}^{N-1}(E_t[\hat{R}_{t+iT,t+(i+1)T}] - \bar{R}_t) - T\sum_{i=0}^{N-1}(E_t[\hat{R}_{t+1+iT,t+1+(i+1)T}] - \bar{R}_t), \end{aligned}$$

again, for all positive integers N. Condition (1) implies that the two series above converge as $N \to \infty$. $E_t[\hat{R}_{t+n}]$ must converge to $\bar{R}_t$, since any other limit would be inconsistent with both (1) and (2) holding. Thus, if the required process for the overnight rate exists, it must equal

$$\hat{R}_t = \bar{R}_t + T\sum_{i=0}^{\infty}(E_t[\hat{R}_{t+iT,t+(i+1)T}] - \bar{R}_t) - T\sum_{i=0}^{\infty}(E_t[\hat{R}_{t+1+iT,t+1+(i+1)T}] - \bar{R}_t). \tag{20}$$

It is easily confirmed that this process satisfies (1) and converges. This completes the proof.

B.2 Proof of Proposition 2

Suppose that the market delivers the m-day rate $R_{t,t+m}$ on day t. We want to show that

$$R_{t,t+m} = \frac{1}{m}\sum_{k=0}^{m-1} E_t[\hat{R}_{t+k,t+k+1}], \quad \text{for all } m \text{ and } t.$$

This will ensure the market delivers exactly the same yield curve as that which results from the traditional implementation of monetary policy.

From Proposition 1, we know that

$$R_{t,t+T} = \hat{R}_{t,t+T} \quad \text{for all } t.$$

Combining this result with the expectations hypothesis, we see that the overnight rate must satisfy

$$\frac{1}{T}\sum_{k=0}^{T-1} E_t[R_{t+k,t+k+1}] = \hat{R}_{t,t+T}, \quad \text{for all } t. \tag{21}$$

Also from the expectations hypothesis, the forward interest rate, on day t, for borrowing and lending from day $t+n$ till day $t+n+1$, equals $E_t[R_{t+n,t+n+1}]$. We know that $\lim_{n\to\infty} E_t[R_{t+n,t+n+1}]$ exists for all t from the assumption in the proposition that the forward overnight rate converges at distant horizons. Using Lemma 1, there is a unique process for the market overnight rate which satisfies (21) and for which $\lim_{n\to\infty} E_t[R_{t+n,t+n+1}]$ exists for all t. The corresponding overnight rate on day t equals $\hat{R}_t$, so that the m-day rate on day t equals

$$R_{t,t+m} = \frac{1}{m}\sum_{k=0}^{m-1} E_t[R_{t+k,t+k+1}] = \frac{1}{m}\sum_{k=0}^{m-1} E_t[\hat{R}_{t+k,t+k+1}],$$

as required.

C The Inter-Bank Market with Sloping Yield Curves

We wish to show that even when the yield curve from 1 to 30 days is not flat, a bank has no incentive to borrow in the inter-bank market to hold additional settlement cash, or lend in the inter-bank market to reduce its holdings of settlement cash; that is, they will choose $d_t = 0$. If this is not the case, there will be pressure from the settlement cash market for interest rates to adjust until banks choose $d_t = 0$ as it is not possible for all banks to be net lenders or net borrowers in the inter-bank market. We calibrate the model presented in the paper to the current New Zealand situation and show that, with a trivial amount of transaction costs, the optimal amount of borrowing is still zero, regardless of the level and slope of the yield curve. We take $N = 5$, $S^* = 5$ million dollars, $\rho^{SC} = 300$ basis points when annualized, $p^D = 90$ basis points when annualized, and $\rho^O = 50$ basis points when annualized. We assume a normal distribution for ε_{t+1} and choose its variance so that it fits the RBNZ's rule — to achieve a settlement cash forecast error of 20 million dollars or less, in four days out of five. We use (11) to determine τ; it equals 3.9 days. Using these numbers, we solve the first order condition (6) and substitute this into the expected profit function (5). Our results imply that for an annualized interest rate spread $(R_t - R_{t,t+30})$ of 100 basis points, which is larger than usual, an individual bank's optimal policy is to lend out 156 thousand dollars, giving the bank an expected gain of 33 cents. For a spread of -100 basis points, the optimal policy is to borrow 162 thousand dollars, giving the bank an expected gain of 34 cents. For a 300 basis point spread, which is much larger than usual, an individual bank's optimal policy is to lend out 455 thousand dollars, giving the bank an expected gain of \$2.89. For a spread of −300 basis points, the optimal policy is to borrow 516 thousand dollars in the inter-bank market, giving the bank an expected gain of \$3.22. These gains are trivial. Given realistic transaction costs, banks have no incentive to hold settlement cash levels different from the RBNZ target (that is, $d_t^* = 0$). This suggests that even very steeply-sloped yield curves, or dramatically changing interest rates, are consistent with equilibrium in the cash settlement market and the RBNZ keeping policy parameters constant.

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