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DOES FOREIGN EXCHANGE INTERVENTION SIGNAL FUTURE MONETARY POLICY?

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ABSTRACT

A frequently cited explanation for why sterilized interventions may affect exchange rates is that these interventions signal central banks' future monetary policy intentions. This explanation presumes that central banks in fact back up interventions with subsequent changes in monetary policy. We empirically examine this hypothesis using data on market observations of U.S. intervention together with monetary policy variables, and exchange rates. We strongly reject the hypothesis that interventions convey no signal. However, we also find that in some episodes, intervention signalled changes in monetary policy in the opposite direction of the conventional signalling story. This finding can explain why in some periods exchange rates moved in the opposite direction of that suggested by intervention.

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I. Introduction

The potential effects of foreign exchange intervention upon exchange rate behavior has been an important issue of debate in both academic and policy–making circles since the end of the Bretton Woods system. As a result, a great deal of research has documented how exchange rates respond to foreign exchange intervention, finding quite mixed results.[1] For example, depending upon the sample period, regressions of exchange rate movements upon intervention have either found strong effects of intervention, no effects of intervention, or even movements of exchange rates in the opposite direction of that suggested by the intervention.

Understanding these varied results clearly requires an explanation for how interventions affect the exchange rate. Since major central banks typically sterilize the monetary effects of interventions, changes in the relative money supplies cannot provide the explanation. One proposition that recognizes that interventions are sterilized is the so–called "signalling hypothesis," first proposed by Mussa (1981).[2] Subsequently, some empirical studies have emphasized that intervention may affect the exchange rate by signalling, and Federal Reserve publications have even claimed signalling to be a reason for intervening.[3]

This explanation posits that intervention signals changes in *future* monetary policy. It says that central banks signal a more contractionary future monetary policy by buying domestic currency in the foreign exchange market today. The expectations of future tighter monetary policy will make the exchange rate appreciate, even though the monetary

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[1]For a survey of this literature, see Edison (1993).

[2]As described in Edison (1993), an alternative explanation is the portfolio balance channel. Overall, the studies discussed in this survey find little empirical support for the proposition that intervention could have an economically important effect through its portfolio effects upon private sector net wealth.

[3]For empirical studies discussing signalling, see Dominguez (1992) as well as other references in the survey by Edison (1993). Signalling has been noted as a reason for intervening in the New York Federal Reserve Bulletin (1991) and has been used as a reason against intervention at Federal Open Market Committee meetings (Record of Policy Actions of the Federal Open Market Committee, August 1989).

effects of the intervention are offset. Of course, this explanation presumes that central banks in fact back up interventions with subsequent changes in monetary policy.

In this paper, we empirically examine this last hypothesis. We test the signalling story using data on market observations of U.S. intervention together with U.S. monetary policy variables from 1985 to 1990. We test whether interventions by the Federal Reserve today imply changes in monetary policy in the future.[4] We then ask whether intervention provides a significant signal of future changes in monetary policy. Interestingly, we strongly reject the hypothesis that intervention provides no information about future monetary policy.

However, intervention can provide useful information about future monetary policy even if current interventions are systematically associated with changes in monetary policy in the opposite direction to the one suggested by the signalling story. For example, *buying* domestic currency in the foreign exchange market today may be correlated with future *expansionary* monetary policy. In this case, interventions may provide a signal in the *opposite* direction to that suggested by the standard signalling story.

To examine this possibility, we develop a methodology in which interventions can signal correctly or incorrectly the change in future monetary policy. Strikingly, when we back out the time–varying behavior of the information process inherent in the intervention signals, we find that most of the information content comes from incorrect signals.[5] Thus, although interventions provide significant information about future monetary policy during our sample, this information is frequently inconsistent with the direction suggested by the signalling hypothesis.

This evidence suggests a possible interpretation for the typical empirical findings

[4]Klein and Rosengren (1991) also examine this question by looking at the relationship between intervention and discount rate changes across the Group of Three countries.

[5]Dominguez (1992) also investigates whether foreign exchange intervention signals correctly future monetary policy by studying the Fed intervention policy in the 1977—1981 period. Interestingly, she also finds that intervention did not always convey the correct information about future monetary policy.

that intervention affects the exchange rate over some periods but not others. Our analysis suggests that intervention will affect the exchange rate differently depending upon whether the intervention was viewed as a correct or incorrect signal. To evaluate this possibility, we examine exchange rate movements on the days following intervention. Strikingly, we find that interventions preceding significant movements in the exchange rate in the direction intended by the authorities were also interventions perceived as conveying correct signals. On the other hand, interventions preceding significant movements in the exchange rate in the opposite direction of the policy intention were perceived as conveying incorrect signals. This evidence suggests that the sample dependent nature of the results from regressing exchange rate movements on intervention may come from the sample dependent nature of the commitments of monetary policy to exchange rate targets.

The rest of the paper is organized as follows: Section II briefly describes the signalling hypothesis of intervention and the general behavior of U.S. monetary and intervention policies from 1985 to 1990. Section III describes the data used in the estimation. As a benchmark case, Section IV estimates a regime-switching process for two indicators of monetary policy without allowing traders to incorporate intervention as a signal. Section V develops a regime–switching process for monetary policy where traders can use intervention as a signal. Section VI examines the reaction of exchange rates to intervention. Finally, Section VII presents the conclusions.

II. The Signalling Hypothesis, Monetary, and Intervention Policy

A. *The Exchange Rate and the Signalling Hypothesis*

The signalling hypothesis is very intuitive. According to standard models of exchange rate determination, the exchange rate depends upon the relative supplies of domestic and foreign monies. If traders in the market are forward–looking, then the exchange rate depends upon the relative money supplies expected in the future as well.

This relationship may be summarized as:

$$(1) \qquad s_t = s(v_t, x_t, E_t x_{t+1}, E_t x_{t+2}, \ldots)$$

where s_t is the exchange rate at time t (domestic currency per foreign currency), x_t is a measure of monetary policy, E_t is the conditional expectation operator, and v_t is the set of all other variables that affect the exchange rate, including past information. The signalling hypothesis says that even though a sterilized intervention to buy domestic currency may not affect current monetary policy x_t, it will lead traders to expect tighter monetary policy in the future. In other words, if x_t represents money supply, then $E_t x_{t+j}$ for some $j > 0$ will be lower than before the intervention, and the exchange rate will appreciate today.

Obviously, the relationship in equation (1) holds for any model of exchange rate determination that includes expectations of future monetary policy. While we will not test any particular exchange rate model in this paper, it is instructive to consider one possible example within this class of models, the asset market model of the exchange rate.[6] Suppose that x_t is the measure of monetary policy while v_t summarizes all variables that affect the exchange rate but are not under the control of the central bank. Then, the exchange rate is the discounted present value of the expected course of future monetary policy and other fundamental variables.

$$s_t = (1-\theta)\sum_{i=0}^{\infty} \theta^i E_t(x_{t+i} + v_{t+i} | \phi_t)$$

where θ is a discount rate and ϕ_t is the information set available to market participants at time t.

The signalling hypothesis presumes that an intervention at time t will be followed by a future change in monetary policy relative to previous expectations. For example, suppose the Fed intervenes by buying dollars and the signalling hypothesis holds true. In

[6]See, for example, Mussa (1982) or Frenkel and Mussa (1980). For a recent empirical study finding that this model may hold over long horizons, see Mark (1992).

this case, defining Ω_t as the information set ϕ_t excluding this intervention, the following relationship would hold:

$$s_t = (1-\theta)\sum_{i=0}^{\infty} \theta^i E_t(x_{t+i} + v_{t+i}|\phi_t) < (1-\theta)\sum_{i=0}^{\infty} \theta^i E_t(x_{t+i} + v_{t+i}|\Omega_t).$$

Since domestic monetary policy will be expected to be lower in the future given intervention, the domestic currency appreciates relative to its level if no intervention had occurred.

Thus, the signalling hypothesis relies on the presumption that the market expects future monetary policy to change upon observing intervention. If traders use information efficiently, they will not interpret intervention as a signal unless monetary policy indeed changes in a systematic way following intervention. We will examine this hypothesis below using data on market observations of foreign exchange market intervention by the Federal Reserve together with measures of monetary policy from September 1985 until February 1990.

At the outset we should emphasize that while the terminology "signalling" has become popular, it may be misleading. The relationship between intervention and future monetary policy changes need not arise from a strategic decision of the Fed to provide any information to the market. The interesting issue is whether interventions provide market participants with useful information about future policy. For the following analysis, we leave aside the issue of whether this information is intentional on the part of the Fed or not but retain the term "signalling" to be consistent with the literature. We will later return to discuss the likelihood that this information signalling was intentional in light of our results.

B. *Monetary Policy and Monetary Aggregates During the Late 1980s*

In order to test the signalling hypothesis, we require a measure of monetary policy over the period of intervention by the Federal Reserve in the 1980s. The Federal Reserve resumed intervention during 1985 after a long hiatus during the first Reagan administration. The impetus for an intervention policy came after the Plaza Meeting in September 1985 when the central banks of the Group of Three countries agreed to intervene more heavily to push down the value of the dollar. We therefore begin our sample at this time. On the other hand, a conflict between the Fed and the Treasury on the issue of intervention led the Fed to quit intervening on its own account during 1990, requiring future interventions during that year to be carried out by the Treasury. For this reason, our study ends in February 1990.

The ideal approach to evaluating monetary policy would be to estimate a reaction function that depended upon key economic variables of importance to the monetary authorities and then consider policy based upon this function. Unfortunately, the brevity of our sample period precludes estimating such a function since it would depend upon variables observed monthly or even quarterly, such as income, inflation, and the trade balance. In light of this constraint, we will directly use monetary policy variables instead. Therefore, it is important to examine whether the behavior of monetary policy indicators during this period was consistent with other accounts of U.S. monetary policy. For this reason, we next provide a brief description of monetary policy behavior and its relationship with monetary indicators.

The stance of U.S. monetary policy changed significantly during the 1980s. For most of the early 1980s, monetary policy was considered quite contractionary as U.S. interest rates hit historic peaks. However, by the beginning of our sample in 1985, the U.S. monetary policy had become relatively expansionary.

Figure 1 shows some measures of monetary policy. The top panel plots weekly observations of M1, M2 together with the Federal Funds rate. As the picture illustrates, the growth rate of M1 accelerated during 1985 and 1986. Over the four quarters of 1986, M1 ballooned at a 15.3 percent growth rate, while M2 rose 9.4 percent. At the same time, the Federal Funds rate trended downward, in tandem with other interest rates. From mid–1984 to the end of 1986, most interest rates declined 5 to 6 percentage points and many short–term interest rates were essentially cut in half. These downward movements were accommodated by two discount rate cuts in April and August of 1986. As Figure 1 shows, the Federal Funds rate reached a trough in early 1987, around the same time that the rate of increase of M1 and M2 began to level off.

Monetary policy was quite different during the following period from roughly 1987 through late 1989. Largely in response to an increase in inflation, the Federal Reserve began tightening reserves in the second quarter of 1987.[7] As a result M1 and M2 rose just 3.5 percent during 1987. The top panel of Figure 1 shows the sharp deceleration in the growth rate in M1. At the same time, the Federal Funds rate began an upward trend that would continue into 1989. This tightening of monetary policy was accentuated with discount rate increases in October 1987, August 1988, and February 1989.

It was not until the second half of 1989 that monetary policy may have eased slightly. Concerned about the sluggish growth of the economy while remaining cautious about inflation, the Federal Reserve began to increase the availability of reserves to depositing institutions and the Federal Funds rate fell more than 1 1/2 percentage points by early January 1990.[8] However, popular press accounts appeared quite divided over whether monetary policy was in fact easing during late 1989, as we will discuss in more detail below.

The narrow measures of monetary aggregates such as nonborrowed reserves tell a similar story of the evolution of monetary policy. The lower panel of Figure 1 depicts nonborrowed reserves, observed only bi–weekly. As the figure shows, nonborrowed reserves moved quite closely with the broader monetary aggregates, M1 and M2, over this period.

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[7]See, the *Economic Report of the President* (1988), page 37.

[8]See "Monetary Policy and Open Market Operations during 1989" in *Federal Reserve Bank of New York Quarterly Review*, Spring 1990, *15*, 43–65.

As a result, nonborrowed reserves suggest a similar pattern of expansionary monetary policy during the early part of our sample and a contraction beginning in 1987. We next describe the behavior of intervention policy during this same period, before turning to the empirical implementation.

C. *Intervention and Monetary Policy*

The U.S. followed an active intervention policy during much of the late 1980s. Table 1 provides some summary information about intervention together with some indicators of monetary policy. As described above, from 1985 through 1986, monetary policy was relatively expansionary. During this period, the Fed intervened on twelve occasions, primarily to sell dollars. For example, after the Plaza meeting in September 1985, the U.S. sold 3.3 billion dollars (from September 23 to November 7 1985).

Intervention activity increased substantially from 1987 through 1989. Until mid 1988, most of the interventions were dollar purchases. For example, in the wake of the Louvre Accord in February 1987, the Fed purchased 30 million dollars against marks to support the dollar on March 11th. The Fed then intervened on a daily basis between March 23 and April 6, 1987 buying another 3 billion dollars. According to Dominguez (1990), the Fed coordinated these interventions with the Bank of Japan and several European central banks. The U.S. continued to intervene in support of the dollar until June 27, 1988.

At this point, intervention policy reversed course sharply, beginning the first of several intervention policy reversals. From June 27 to September 26, 1988, the U.S. sold 5 billion dollars. However, this policy was reversed in the last quarter of 1988, during which the Fed bought 2.6 billion dollars. On January 6, 1989, policy was once again reversed as the Fed renewed heavy dollar selling intervention in the foreign exchange market. Thus, the Fed was active on both the buying and selling side of the foreign exchange market during the period, as Table 1 summarizes.[9]

III. The Data

In order to examine the signalling hypothesis, we require both a measure of monetary policy and public observations of intervention. In this section, we discuss the data issues involved with these measures.

First, we must address the issue of which measure of monetary policy to use. There is certainly no agreement in the literature about which indicator best reflects the stance of monetary policy. A plethora of papers use broad measures of money supply as the indicators. For example, Mishkin (1981,1982) and Cochrane (1989) use M1; while Melvin (1983) uses M2, and Reichenstein (1987) uses both M1 and M2. However, some authors such as Christiano and Eichenbaum (1992a,1992b) and Strongin (1992), have argued that movements in broad monetary aggregates can be misleading measures of monetary policy since they confound money demand shocks with money supply shocks and have suggested using nonborrowed reserves as the indicator of monetary policy. Still others, such as Bernanke and Blinder (1992) and Goodfriend (1992), have argued for the Federal Funds rate as the monetary indicator. They claim that movements in the Federal Funds rate are genuine policy changes, not simply endogenous responses of the Federal Funds rate to changes in the economy. According to this view, reserve demand shocks are fully accommodated by open market operations, so that these shocks have no effect on the Federal Funds rate, which is mainly determined by policy decisions.

To check whether our results are robust to different measures of monetary policy we will test the signalling hypothesis using different measures of monetary policy. Given the above discussion, the obvious candidates are nonborrowed reserves, M1, and the Federal Funds Rate. Unfortunately, narrow monetary aggregates such as the monetary base and

[9] Dominguez and Frankel (1992) provide a detailed survey of intervention over this period.

nonborrowed reserves are only available bi–weekly. Since our sample is short, we cannot use bi–weekly series and therefore confine the study to M1 and the Federal Funds rate. Despite this limitation, we will show below that the results are quite similar between the two extreme measures examined. This finding taken together with the evidence in Figure 1 suggests that the results are likely to be similar for nonborrowed reserves as well.

The specific series we study are the Federal Funds rate and M1 obtained from the Federal Reserve Board data bank. The Federal Funds rate is the weekly average of the daily rate, while M1 is the average stock of money for the week ending on Mondays.

We now consider the intervention data. To test the signalling hypothesis, we must use information known to traders. Although traders frequently know when central banks are intervening, monetary authorities rarely provide information about the magnitudes at the time of intervention. Furthermore, central banks occasionally try to conceal their intervention operations. These interventions will usually not be recognized by the market and hence it seems highly unlikely that these interventions could be signalling anything at all.

For these reasons, we use an intervention series based upon reports by traders on the day of the intervention. These data were collected from accounts in the *Wall Street Journal*, *The New York Times*, and *The Financial Times*.[10] This data series consists of days in which the Federal Reserve was observed intervening by traders. These days are further decomposed into days when the Fed either bought or sold dollars.

IV. A Markov–Switching Model for Monetary Policy without Intervention as a Signal

As described above, monetary policy in the United States during the late 1980s appeared to alternate between relatively expansionary and contractionary regimes. To

[10] Dominguez and Frankel (1992) and Klein (1992) find that newspaper accounts were largely accurate in picking up days of actual intervention during this period. Similar to those studies, newspaper accounts in our sample tend to understate the number of days of intervention due to concealed interventions, while counterfactual reports of intervention are rare.

evaluate whether intervention provided a significant signal about this policy change, we will first consider how expectations of this monetary change would have evolved if market participants did not use intervention as a signal. This model will provide a useful benchmark for comparison when we incorporate intervention as a signal in the next section.

To capture the changes in monetary policy behavior, we estimated a univariate process for the monetary indicators allowing their evolution to follow two regimes, $R_t = i$, for $i = 0,1$. Conditional upon each of these regimes, the process is autoregressive of order s in first differences as given in the following equation:

$$(2) \qquad \Delta x_t = \delta_0^i + \sum_{m=1}^{s} \delta_m^i \Delta x_{t-m} + \epsilon_t \qquad\qquad \epsilon_t \sim N(0,\sigma^2)$$

where x_t is either the logarithm of money supply, m_t, or the Federal Funds rate, f_t. Also, δ_0^i is the drift of the monetary indicator in regime i, δ_m^i are the parameters of the AR process for Δx, and ϵ_t is the innovation in monetary policy. The innovations are assumed iid and normally distributed with variance σ^2 in both regimes. For expositional purposes, we will define Regime 1 as the relatively expansionary monetary regime. Hence, if money supply is the monetary indicator we normalize $\delta_0^1 > \delta_0^0$, while for the Federal Funds rate, we choose regimes such that $\delta_0^1 < \delta_0^0$.

The probability of switching between these two regimes is governed by the following stationary probability matrix.[11]

(3)

	$R_{t-1}=1$	$R_{t-1}=0$
$R_t=1$	$(1-\lambda)$	λ
$R_t=0$	λ	$(1-\lambda)$

Traders do not observe these regimes, R_t, directly but must infer them from the

[11]We also estimated a more general version of the model where the variances and the transition probabilities were state–dependent. Likelihood ratio tests could not reject that the variances and the probabilities were the same and we therefore present only this more parsimonious specification in the text.

current information set. For this benchmark model without intervention as a signal, we simply assume that the traders' information set in confined to current and past observations on the monetary indicator. This information set is given by $\phi_t = \{\Delta x_t, \Delta x_{t-1}, \ldots, \Delta x_1\}$ for alternatively, x=m (log(M1)) and x=f (Federal Funds rate). For this benchmark model, we can use Hamilton's (1988) non–linear filter to estimate the process in equation (2) and (3) using either weekly data for U.S. M1 money supply or the weekly average Federal Funds rate for the period September 23, 1985 to February 2, 1990. Details of this procedure are provided in the appendix.

Table 2 reports the results of this estimation. In the top panel, we report the results using M1 as the policy variable. Based upon time series analysis, we found that M1 is best described as a random walk process with changing drift coefficients. Interestingly, the model indeed captures an expansionary and a contractionary monetary regime. During the expansionary monetary regime, money supply grows at 0.33 percent per week while in the contractionary monetary regime money supply grows at only 0.048 percent per week. Another feature of the model is that the transition probability, λ, is very small at about 1 percent, indicating that both regimes display considerable persistence. In fact, the estimated probability implies that the expected duration of the monetary regimes is approximately 106 weeks.

Notably, the estimates using the Federal Funds rate display similar characteristics, as reported in the bottom panel of Table 2. The first difference of the Federal Funds rate is best described by a first–order autoregressive process with regime–dependent drift and AR(1) coefficient. In Regime 0, the drift is positive ($\delta_0^0 = 0.035$) while in Regime 1 it becomes negative ($\delta_0^0 = -0.044$). This process of alternating positive and negative trends in the Federal Funds growth rate supports the notion that monetary policy alternated between contractionary and expansionary monetary regimes over the period. Similar to the results using money supply, the implied probability of switching regimes using the Federal Funds rate as indicator is very small. However, in this case, the expected length of the monetary regimes is slightly shorter at 77 weeks.

As noted above, the estimates assume that traders do not known with certainty the monetary regime. On the other hand, traders can make inferences about the monetary regime using the information available on the monetary indicator. For example, they can assign probabilities to whether the process was in Regime 0 or 1 at any given date t based upon currently available information. In other words, as the information set ϕ_t changes, so do traders' assessed probabilities of the current regime as well as their priors of the regime in the next period through the relationship:

$$\mathrm{Prob}(R_t=1|\phi_{t-1}) = \mathrm{Prior}(R_t=1),$$

where $\mathrm{Prob}(z_t|\phi_t)$ is the probability of z conditioned on the time t information set, ϕ_t, and $\mathrm{Prior}(z_t)$ is the prior probability of z for traders entering period t. Using our estimates as well as the evolution of the monetary indicator variables, we can generate these probabilities.

Figure 2 shows these probabilities. The top panel shows the implicit prior of being in an expansionary monetary regime using money supply as the monetary policy indicator, while the bottom panel reports the probability implicit in the Federal Funds rate model. Strikingly, the predictions of the model with both indicators are consistent with the stylized evidence of monetary policy discussed above. In particular, the probability of an expansionary regime is quite high through much of 1986, but then drops to below 50 percent during early 1987. Most of the latter part of the sample is characterized by a fairly low probability of the expansionary regime. If we use the criterion of assigning observation t to Regime 1 if the conditional probability is larger than 1/2, then these probabilities classify the following observations as belonging to the expansionary monetary regime.

Expansionary Monetary Regime Episodes

Money Supply (M1)	Federal Funds Rate
1986:14—1987:02	1985:41—1985:43
1987:17—1987:18	1985:45—1985:49
1987:44—1987:44	1985:51—1987:18
	1989:31—1989:39
	1989:42—1990:05

Interestingly, the two different classifications of monetary policy in the last semester of 1989 by the two different measures appears consistent with the confusion over policy in the popular press due, in part, to conflicting statements by the various government officials.[12] In early October, reports of an easing of monetary policy were mixed with contradictory statements that policy had not eased.[13] The following week Fed Chairman Greenspan made statements on a trip to Moscow that the markets interpreted as a message that tight monetary policy would be maintained, leading to a rise in the dollar.[14] However, the next day, traders appeared divided over whether tight or easy monetary policy would ensue.[15] The perception that monetary policy had remain relatively contractionary was reinforced by Chairman Greenspan's statements in congressional testimony. The London *Financial Times* stated, "Mr. Greenspan's [...] comments were seen by observers as highlighting the Fed's current caution about any early substantial easing of U.S. monetary policy and of interest rates" ("Greenspan Warns that U.S. Inflation Rate is Too High," London *Financial Times*, October 26, 1989). Thus, the conflicting evidence from our two

[12]Dominguez and Frankel (1992) also argue that there was some confusion over the direction of monetary policy during late 1989.

[13]For instance, an article in the London *Financial Times* reported that the most recent FOMC meeting record of policy actions suggested both a "directive that tilted toward monetary easing" and that some members objected stating "a bias in the new directive towards ease might lead to a misreading of policy in the context of an unacceptably high rate of inflation" ("Evidence Mounts of Turn in Dollar Trend," London *Financial Times*, October 9, 1989).

[14]"Tokyo Discount Rate Rise May Not Be Enough" in London *Financial Times*, October 12, 1989.

[15]For example, the London *Financial Times* stated, "traders were divided on whether the Federal Reserv had eased its monetary stance" ("Rates Up On Lawson," *Financial Times*, October 23, 1989).

different measures of monetary policy also appears consistent with the contradictory information received by market observers at the time.

Overall, our estimates are consistent with other evidence of U.S. monetary policy discussed in Section II. During 1985 through 1986, monetary policy was relatively expansionary. Except for isolated periods, monetary policy was considerably more contractionary from 1987 to 1989.

V. Is Intervention a Signal of Future Shifts in Monetary Policy?

The evidence above, consistent with discussions in both official documents and the popular press, suggests that monetary policy shifted from an expansionary regime to a contractionary regime during the sample period. In this section we ask whether intervention provided a significant signal of this shift in policy. We begin by describing the evolution of expected future monetary policy with intervention as a signal. We then discuss the methodology for estimating the model as well as the results.

A. *Expected Future Monetary Policy with Intervention as a Signal*

We will address the question of whether intervention provides a signal of future monetary policy in two different ways. First, does intervention provide a signal of future monetary policy at all? For example, intervention may have nothing to do with future monetary policy, so that traders would disregard information about intervention when forming forecasts. To test this hypothesis, we will examine whether intervention at some lag k is useful for predicting the current monetary regime, R_t. We will shortly describe more precisely what we mean by past intervention. For the present, we will simply define the event of this past intervention at t–k as $S_t=1$ and the event of no intervention at t–k as $S_t=0$. In this context, the first way to ask if intervention signals future monetary policy is to ask whether S_t conveys any information about R_t.

A second way we will ask the question is: if intervention *does* provide information about future monetary policy, does intervention signal the correct direction of future policy? For example, interventions to buy dollars would suggest that the Federal Reserve is more concerned about the value of the U.S. dollar and might reflect an intention to pursue more contractionary monetary policy in the future. We will refer to this type of intervention signals as "Correct Signals." On the other hand, an intervention to buy dollars may also be an attempt to bolster the value of the dollar when monetary policy is actually expansionary in the future. We call these types of intervention signals "Wrong Signals."[16] Even though these interventions signal the wrong direction of future monetary policy, systematic interventions of this type can be useful to traders in assessing the course of future policy.[17]

A difficulty in assessing the nature of these two types of signals is that policy intentions may vary over time with changing monetary leadership. There are several reasons to suspect that these intentions may have changed during our sample period. First, there were changes in governors of the Federal Reserve Board. Second, the opinions of the Board members toward intervention appeared to change over time as evidenced by records of policy actions of the FOMC. And, finally, the relationship between the Treasury and the Federal Reserve evolved as well, as the Board became more concerned about the nature of signalling in late 1988 and 1989.[18]

In order to incorporate some of the dynamics of potential changes in types of signals as viewed by the market participants, we allow for different states of information signals arising from intervention.[19] For purposes of exposition, suppose first that the monetary

[16] In adopting this terminology, we should emphasize that the words "correct" and "wrong" relate only to whether the intervention is consistent with the signalling story or not. It is not intended to convey any judgement about the appropriateness of the policy.

[17] Of course, a recognition by the market that signals are in the opposite direction of future policy would be detrimental to the usefulness of intervention on the part of the central bank. An example of this behavior during the sample will be discussed below.

[18] We will discuss these issues in more detail in conjunction with the results.

[19] The model described in this section is a generalization of the model developed in Kaminsky (1991).

authority intervenes every period (S_t=1 for all t). At the time of intervention, t–k, the authorities may have been following a "correct" signalling policy defined by the regime C_t where interventions signal correctly the direction of future policy, or a "Wrong" policy defined by W_t where interventions signal a change in monetary policy in the opposite direction. In keeping with the Markov switching process for monetary policy above, we allow these states to evolve according to the transition probability matrix:

(4)

	$C_{t-1}=1$	$W_{t-1}=0$
$C_t=1$	$(1-p)$	p
$W_t=0$	p	$(1-p)$

Equation (4) describes the transition probability between correct and wrong signalling regimes under the assumption that the monetary authority signals –through intervention– every period. However, we have seen in Table 1 that the Fed chose not to intervene (S_t=0) for long stretches of time during the period under examination. For example, there was essentially no intervention by the Fed during 1986. If periods with and without signalling alternate, it is necessary to specify the dynamics across these states too. It seems implausible that traders who had not observed intervention for such a long period of time would simple update the probability of the correctness of the signal according to equation (4) based upon previous interventions that had taken place such a long time ago.

It appears more reasonable to suppose that traders view the probability of correct or wrong signal differently when intervention does not occur for some time. To allow for this possibility, we treat the probability of the correctness of the intervention signal if intervention occurs after a period of no intervention as:

(5) $$\text{Prob}(C_t \mid S_t=1, S_{t-1}=0) = q$$
$$\text{Prob}(W_t \mid S_t=1, S_{t-1}=0) = (1-q)$$

In other words, if traders observe intervention potentially useful for understanding the current regime, $S_t=1$ after no intervention in the previous period, $S_{t-1}=0$, they believe that the intervention will be correct with probability q but wrong with probability (1–q).

We can now combine both the processes in (4) and (5) to provide a full transition process of the signal given past intervention.[20] This process is given by:

(6)

		$S_{t-1}=1$		$S_{t-1}=0$
		C_{t-1}	W_{t-1}	
$S_t=1$	C_t	$(1-p)$	p	q
	W_t	p	$(1-p)$	$(1-q)$

Hence the complete signalling model consists of equations (2) and (3), and (6).

To specify the link between the potential evolution of signals in (6) and the process for the monetary indicators in (2) and (3), we need to incorporate one last piece of information: whether the intervention k periods ago was a dollar sale or purchase. For this purpose, define an observation of intervention at time t–k as $I_{t-k}=1$ if the Federal Reserve intervened by selling dollars or $I_{t-k}=0$ if it intervened by buying dollars. A "Correct" signal at time t–k about the monetary regime in some future period t implies a positive

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[20]Note that since intervention is observed with a lag, S_t is known at time t. Therefore, no transition probability need be specified between S_t and S_{t-1}. If S_t were uncertain, however, we could easily incorporate this transition. In particular, let $\text{Prob}(S_t=j \mid S_{t-1}=i) = \pi_{ji}$ Then the transition matrix in (6) would instead be:

		$S_{t-1}=1$		$S_{t-1}=0$
		C_{t-1}	W_{t-1}	
$S_t=1$	C_t	$(1-\pi_{01})(1-q)$	$p(1-\pi_{01})$	$r\pi_{10}$
	W_t	$(1-\pi_{01})q$	$(1-p)(1-\pi_{01})$	$(1-r)\pi_{10}$
$S_t=0$		π_{01}	π_{01}	$(1-\pi_{10})$

relationship between $I_{t-k}=1$ and $R_t=1$, or more generally between $I_{t-k}=i$ and $R_t=i$. On the other hand, a "Wrong" state W_t implies a correspondence between $I_{t-k}=i$ and $R_t=j$, where $j\neq i$. More formally, $C_t = \{I_{t-k}=i|R_t=i;\ i=0,1\}$ and $W_t = \{I_{t-k}=i|R_t=j;\ i\neq j,i,j=0,1\}$. Note that the full information set of traders now also includes the occurrence of intervention and its direction; i.e., $\phi_t=\{\Delta x_t,S_t,I_{t-k},...\Delta x_1,S_1,I_{1-k}\}$.

The evolution of the intervention signal together with the monetary regime determine expected future monetary policy. For example, note that the monetary regime affects expectations of monetary policy since by (2) and (3), the expected monetary policy next period is given by:

$$(7)\qquad E_t\Delta x_{t+1}= (\delta_0^0+\sum_{j=0}^{s}\delta_j^0\Delta x_{t-j})[1-\text{Prior}(R_{t+1}=1)]+(\delta_0^1+\sum_{j=0}^{s}\delta_j^1\Delta x_{t-j})\text{Prior}(R_{t+1}=1)$$

These priors are in turn transition probabilities weighted averages of the posterior probabilities of being in each regime based upon information at time t including the intervention signal, S_t, the direction of the intervention, I_t, and the monetary indicator, x_t. The appendix gives details about the full evolution of the joint system of intervention, signals, and monetary indicators.

B. *Empirical Results*

We now describe briefly the estimation of the system described above. Using the equations for the priors of the monetary regime, the conditional posteriors in terms of the likelihood function and the previous period priors, as well as the evolution of the probabilities of the signalling regime, we can construct the joint likelihood function of current indicators of monetary policy and lagged intervention. The sample log likelihood is equal to:

$$(8)\qquad \ln(f(\Delta x_t,S_t,I_{t-k},..,\Delta x_1,S_1,I_{1-k})) =$$

$$=\sum_{t=1}^{T}\ln(f(\Delta x_t, S_t, I_{t-k} \mid \Delta x_{t-1}, S_{t-1}, I_{t-k-1}, \ldots, \Delta x_1, S_1, I_{1-k}))$$

We estimated this model by maximizing this function numerically with respect to the unknown parameters: δ_0^0, δ_0^1, δ_j^0, δ_j^1, σ^2, λ, p, and q. For the initial period, we assumed a diffuse prior on both the monetary regime, and the nature of the signal. Thus we set the initial priors (Prior($R_1=1$), Prior($C_1 | S_1=1$)) equal to 0.5.

To estimate the model, we also needed to make an assumption about the lag at which past intervention is useful for predicting the current monetary regime. For a signal to provide valuable information to traders, it must precede monetary policy changes in a proximate and consistent manner. Since the Fed can provide the public information about monetary policy intentions through other methods such as statements in the record of policy actions of the FOMC published approximately every six weeks, it seems unlikely that the lag of this signal can be very long. We therefore experimented with different values of k. In particular, we estimated the model with k=1 week and k=3 weeks. Since the results were essentially the same, we just report the results with k=1.[21]

Table 3 reports the estimation results. In estimating the signalling models we imposed the result found in Table 2 that money supply follows a random walk with a drift and that the first difference of the Federal Funds rate follows an AR(1) process. Consistent with our findings for the model without intervention as a signal in Table 2, the growth rate of money in the expansionary regime is significantly higher than the growth rate in the contractionary regime. In particular, δ_0^1 is about 0.4 percent weekly or about 10.8 percent annualized while δ_0^0, its counterpart in the contractionary regime, is only about 0.06 percent weekly or 3 percent annualized in the contractionary monetary regime. The results using the Federal Funds rate also support the hypothesis of a switch in monetary regime, although the estimates are less precise. Still, we find that in Regime 1,

[21]Of course, if intervention provides information about monetary policy at a one week horizon, by iterating the Markov process forward, it also provides forecasts of monetary policy regimes in any future period.

the drift rate is negative and equal to -0.025, while in the contractionary Regime 0, the drift is a positive 0.017. As before, the transition probability of the monetary regime, λ, is quite small.

The signalling model provides two new parameters: the transition probability between the "Correct" and "Wrong" signalling regimes, p, and the probability of a "Correct" signalling regime given no recent interventions, q. As Table 3 shows, the transition probability p is close to zero. On the other hand, the probability of a correct signalling regime given no past intervention, q, is larger but less than 0.5.

A convenient feature of our framework is that we can test the signalling hypothesis in a straightforward and intuitive way. Specifically, if the authorities appear to switch between correct and wrong signals with even odds, then observations of intervention will convey no meaningful signal of future monetary policy. Formally, this behavior is identical to a transition probability between the correct and wrong signalling states, p, that equals 1/2. Also, when interventions have not occurred recently, a new intervention will not convey any information if the probability of a correct or wrong signal is also 1/2. Thus, a test of the null hypothesis that intervention provides no signal is a test of the constraint $p=q=1/2$.

In this case the joint density function for Δx_t, S_t, and I_{t-k} in (8) will just be a function of the marginal density function for the monetary indicator (money supply or the federal Funds rate) alone:

$$f(\Delta x_t, S_t, I_{t-k} \mid \Delta x_{t-1}, S_{t-1}, I_{t-k-1}, \ldots, \Delta x_1, S_1, I_{1-k}) = 0.5 f(\Delta x_t \mid \Delta x_{t-1}, \ldots, \Delta x_1).$$

In addition, the conditional probabilities of monetary regimes will depend only upon past values of the monetary indicator. From these facts, we can construct the likelihood ratio test of the constrained and unconstrained models,

$$(9) \quad LRT = 2\,\{\ln(f(\Delta x_t, S_t, I_{t-k}, \ldots, \Delta x_1, S_1, I_{1-k})) - [\ln(f(\Delta x_t, \ldots, \Delta x_1)) + n\ln(1/2)]\}$$

where n is the number of times there was intervention in the sample (i.e., $n = \sum_{t=1}^{T} S_t$). Since the difference between the two models involves two constraints ($p=1/2$ and $q=1/2$), the likelihood ratio test is distributed as χ^2 with two degrees of freedom.

Table 3 reports this test statistic along with its marginal significance level in parenthesis. As the table shows, the likelihood ratio test is quite large and the null hypothesis is strongly rejected at all standard significance levels. Thus, intervention provides a significant signal about future changes in monetary policy.

C. *The Evolution of the Monetary Regimes and Perceptions of Policy Intentions*

The estimates of the model provide an evolution of the probabilities of the expansionary monetary regime as well as of the correctness of the signal. Figure 3 depicts the prior probabilities of the expansionary regime ($R_t=1$) based upon lagged intervention and the previous period's monetary indicator (money supply in the top panel and Federal Funds rate in the bottom panel). This series is plotted along with the prior probabilities of correct signals.

When money supply is the indicator of monetary policy, the probabilities of the expansionary regime follow a pattern similar to the ones without intervention as a signal, described in Figure 2. The probability of an expansionary regime increases during the first part of the sample and then remain high through the second week of 1987. Thereafter, the probability of an expansionary regime is low with occasional temporary increases, such as during the week following the October 1987 U.S. stock market crash. When the intervention signal is used, however, the probabilities of being in an expansionary monetary regime seem to pinpoint monetary policy with greater precision.

On the other hand, when the Federal Funds rate is used as the monetary indicator, the path of the probabilities of being in an expansionary monetary regime changes more significantly when intervention is used as a signal. For example, while the probabilities excluding intervention in Figure 2 classified the second semester of 1989 as an expansionary monetary regime, the probabilities including intervention in Figure 3 do not. Strikingly, the probabilities of an expansionary regime using intervention as a signal given in Figure 3 are much more similar across measures of monetary indicators than are those ignoring intervention given in Figure 2. Even the end of 1989 is now perceived as a contractionary regime by both measures. The heavy intervention to sell dollars appeared to be a "leaning–against–the–wind" policy in response to an appreciating dollar. The combination of this information in intervention together with monetary policy measures helped to classify monetary policy as contractionary. Below, we discuss this period in more detail.

Using the criterion described before the probabilities of being in an expansionary monetary regime classify the observations as follows:

Expansionary Monetary Regime Episodes

Money Supply (M1)	Federal Funds Rate
1986:19–1987:02	1985:41–1985:49
1987:17–1987:19	1985:50–1987:35
1987:44–1987:44	

Figure 3 also plots the probability of a "Correct" signal as circles. Since intervention can provide a signal only after intervention occurs, this series is not continuous. As we have not restricted the probability of a "Correct Signals" regime to depend on previous "signalling strategy" when intervention had not occurred in the recent past, the prior probability of a correct signal during solitary weeks of intervention is equal to 0.423 =q when money supply is the monetary indicator, and 0.302 =q when the Federal funds rate is the monetary indicator as reported in Table 3. Interestingly, periods of concentrated intervention generally show the persistence of "Correct" or "Wrong" states captured by the estimation. The only exception to the high persistence in correct signals was the six–week episode of intervention in the fall of 1987 when the probability of a correct signal dipped down near zero but upon observing several more weeks of money supply, increased to near one. Even this exception is not observed when the Federal Funds rate is used as indicator.

Most of the intervention took place when monetary policy was contractionary. During some of these intervention episodes, such as the one after the Louvre Accord, the Fed intervened to support the dollar presumably signalling a contractionary monetary stance. It is these episodes of intervention that the model classifies as belonging to the "Correct" signalling regime. But intervention did not always signal a tight monetary policy. For example, when the Federal Reserve intervened in 1989, it always sold dollars (see Table 1) seemingly signalling an expansionary monetary regime according to the signalling hypothesis. Similarly, the dollar sales by the Federal Reserve in the second semester of 1988 would have signalled an expansionary monetary regime in contrast to the actual monetary policy. The model captures this apparent contradiction between intervention and monetary policy as a "Wrong" signalling regime from the second semester of 1988 through 1989.

To examine the evolution of the correctness of the signals more closely, Figure 4 plots the updated posterior probabilities based upon observations of monetary policy within that week. Thus, the posterior probabilities allow us to see how traders updated their priors of the correctness of the signal after viewing the actual change in money supply or Federal Funds rate during the period. In addition to the same concentration of signals found before, Figure 4 shows that periods of low priors of the correct signalling regime were frequently followed with zero probability of correct signalling after observing the monetary indicator during the period, and vice versa. The intervention episodes beginning in early 1989 particularly display this pattern.

D. *The Estimates in Light of Other Measures of Federal Reserve Policy*

We next consider additional information about Federal Reserve behavior over this period both to verify our results and to offer a different perspective of their interpretation.

As monetary policy became more contractionary and remained so well into 1989, this tightening led to a relative strengthening of the dollar. Due to concerns by the Treasury about this strengthening, the U.S. intervened heavily to sell dollars for much of this period. Starting on June 27, 1988 the U.S. sold dollars in the foreign exchange market, totalling 5 billion dollars by September 26. A second round of heavy dollar selling began on January 6, 1989. Since monetary policy remained relatively tight for this period, this combination of policies indicates that interventions were systematically in the opposite direction of the signalling story. This pattern shows up as "Wrong" signals in our estimates.

Even more strikingly, documents of the Federal Reserve also imply precisely the pattern of signalling we found above. During early 1989, debate increased among the governors on the Federal Reserve Board concerning intervention and the appropriateness of its signal toward monetary policy. By the FOMC meeting on May 16, 1989, intervention had become an important issue of discussion as the large purchases of foreign currency assets by the New York Federal Reserve Bank had increased holding of these assets beyond the legal limit. Governor LaWare dissented in a vote to extend the limit on foreign currency holdings to "convey skepticism about intervention" (Record of Policy Actions of the FOMC, May 16, 1989). The continued dollar sales meant that intervention was again an issue at the June 14 FOMC meeting, when the limit on foreign currency holding had to be increased again. By the August 22 FOMC meeting more governors were critical of the intervention policy. Governors Angell and Johnson dissented on a move that would allow further intervention stating "intervention confuses market participants concerning the policy commitment toward price stability" (Record of Policy Actions of the FOMC, August 22, 1989).

Due to this controversy, most of the interventions by the end of 1989 were no longer conducted on the Federal Reserve's account, but rather on the Treasury's account. From a total of dollar–selling intervention in the first four months of 1990 of 2.4 billion dollar, only 675 million dollars were on the Federal Reserve's own account. With growing concern among FOMC members about conflicting signals sent to the market through intervention, from March 5, 1990 through the rest of the year all interventions were for the Treasury's account alone.

This period of conflict between the Treasury and the Fed did not go unnoticed by the markets or the popular press. In mid–October 1989, a newspaper reported that Treasury Secretary Nicholas Brady "conceded the existence of differences over interest rate and dollar policy between the administration and Federal Reserve."[22] The potential impac of these differences also arose in the late October congressional testimony of Chairman Greenspan. Following reports of disputes among policymakers, including public dissent by two Fed governors, he pointed to the limits on how far intervention in the foreign exchange market could influence the level of the dollar.[23]

Clearly, this account of the Federal Reserve's concern about "Wrong" signals accords with our estimates above. This evidence and our estimates indicate the Federal Reserve was unlikely to be intentionally signalling future monetary policy changes. Rather, it appears more likely that interventions were a reaction to the strengthening of the dollar, while the Fed continued maintaining a contractionary monetary policy. Thus the "signal" of intervention in the opposite direction from actual future monetary policy was probably unintentional.

Despite the likelihood that these signals were not intentional, we have shown that intervention provided statistically significant information about the course of future monetary policy. If so, it seems likely that market participants would have incorporated information about whether the intervention was based upon "Correct" or "Wrong" information states. In the next section, we provide suggestive evidence that foreign

[22]"Brady Plays Down Policy Rift," London *Financial Times*, October 13, 1989.

[23]"Greenspan Warns That U.S. Inflation Is Too High," London *Financial Times*, October 26, 1989.

exchange market traders were informed about the potential signal in intervention.

VI. Reaction of Exchange Rates to Intervention: Some Suggestive Evidence

According to the simple model considered in Section II, the exchange rate depends upon current and expected future changes in monetary policy as well as other fundamental variables not controlled by the central bank. Repeating for convenience, the basic equation was given as:

$$s_t = (1-\theta)\sum_{i=0}^{\infty}\theta^i E_t(x_{t+i}+v_{t+i}|\phi_t).$$

According to this model, an intervention of dollar sales based upon a "Correct" signal will lead to a higher expected future monetary policy, $E_t x_{t+i}$, relative to no intervention. Of course, since the exchange rate depends upon the current and expected future levels of other variables, v_t and $E_t v_{t+i}$, as well as current monetary policy given by x_t, and since interventions may arise in response to these variables, intervention will not necessarily move the exchange rate at all. However, to the extent that "Correct" signalling interventions do move the exchange rate, rational traders would tend to depreciate the value of the dollar following dollar sales. Thus, if we looked at movements in the exchange rate on the day following "Correct" intervention, we would expect to find either no significant effect or else a significant movement in the direction intended by the intervention (i.e., appreciation if dollar purchases, depreciation if dollar sales).

On the other hand, if interventions are perceived as conveying information that future monetary policy will be in the opposite direction, then the same logic applies in the reverse. Dollar sale interventions will lead traders to expect tight monetary policy in the future. This new information will either not be sufficiently significant to move the dollar or else will significantly push the dollar up.

Thus, the tendency for intervention to affect the exchange rate will depend upon whether the information is perceived as in the "Correct" or "Wrong" direction. At a suggestive level, we would expect that exchange rate movements following "Correct" interventions should tend to induce exchange rate movements in the direction implied by the operation if at all, while "Wrong" interventions should tend to induce exchange rate movements in the opposite direction, if at all.

To consider this relationship, we examined the response to intervention news of the Deutsche mark/dollar and the Japanese yen/dollar rate. We used daily data on intervention and exchange rates. Exchange rates are quoted at noon in the New York market.[24] The reaction was measured as the change in the relevant exchange rate on the day of the intervention. Since the discussion above revealed that exchange rates should react differently depending on the information state, we further divided the sample between episodes with correct and incorrect signalling as indicated by the prior probabilities of the Federal funds rate model reported in Figure 3 (the results based upon M1 were similar).

Table 4 reports the results based upon the different years, decomposed according to dollar selling and dollar buying interventions. The evidence is remarkably consistent with the implications of the analysis above. For "Days of Selling Dollars Intervention" under "Correct Signals," the dollar either depreciated significantly as in 1985, or else was not significantly changed. By sharp contrast, when these same dollar sale interventions were perceived as "Wrong Signals" (under the third and fourth columns), the exchange rate significantly appreciated in every year except 1985 when the effect was insignificant.

Further evidence of this phenomenon is provided by the dollar purchases intervention summarized in the last four columns of Table 4. When the signal was viewed as correct, the intervention lead to a significant appreciation in the dollar relative to the yen in 1988 as would be predicted by the model. In all other cases, the relationship is

[24]Most U.S. intervention takes place in the morning to have a stronger impact during the overlap period when European markets are still open.

insignificant. On the other hand, when the signal was viewed as incorrect, dollar buying interventions led to significant dollar depreciation against both currencies in 1987 and insignificant depreciation in 1988.

In all of these cases, significant movements in the exchange rates following interventions depended crucially upon whether the interventions were viewed as conveying correct or incorrect signals of future monetary policy. This evidence suggests an interpretation of the typical finding in the literature that the effectiveness of intervention appears to depend heavily upon the sample period.[25] During periods when intervention is viewed as consistent with the direction of future monetary policy, the regression of exchange rate changes on intervention may provide statistically significant coefficients in the direction suggested by effective intervention policy. However, for other periods, the evidence may be insignificant or even in the wrong direction. The evidence in this paper suggests that the sample dependent nature of this evidence comes from the sample dependent nature of monetary and intervention policy.

VII. Concluding Remarks

This paper investigated whether U.S. foreign exchange interventions during the late 1980s signalled a change in monetary policy. To address this question, we developed a methodology allowing intervention to signal shifts in monetary policy regimes. We tested and rejected the hypothesis that intervention provides no signal of future monetary policy. Thus intervention was informative about future monetary policy over the period.

We also showed that this evidence should not be constructed as an argument in favor of intervention, however. Indeed, the estimates indicate that interventions signalled future monetary policy in the *opposite* direction from the signalling hypothesis for much of the period. For example, dollar sales in the foreign exchange market were frequently

[25]See, for example, Dominguez and Frankel (1992).

followed by contractionary monetary policies. Furthermore, if interventions did not occur for some period of time, a new episode of intervention was viewed as only 30 percent to 43 percent likely to provide a signal in the correct direction.

When traders view intervention as signalling monetary policy changes in the opposite direction, these interventions are useful for predicting the future. However, when intervention is perceived by the market as providing information that monetary policy will move in the opposite direction than suggested by the intervention, the implied movements in the exchange rate will also tend to move perversely. For example, using data on exchange rate changes on the days following interventions viewed as conveying incorrect signals, all significant movements in the exchange rate were in the opposite direction intended by the intervention. As a result, these types of interventions can be very costly in terms of the required intervention volume. This problem was evident during 1989 and 1990 when dollar sales intervention in the face of continued tight monetary policy forced the Fed to acquire foreign currency holding beyond its legal limit.

The approach taken in this paper suggests several directions for future research. First, we assumed that if the Fed has not intervened for a period of time, traders do not use past information about the credibility of intervention as a signal. However, past information about whether central banks signalled correctly may potentially be important. Second, we have assumed that the transition probabilities of changes in the credibility of the signals are constant over time. In reality, these probabilities are likely to be functions of variables such as the state of the economy. Therefore, future research should address this possibility. Third, our short sample period precludes considering a reaction function that depended upon real variables that are only available at longer time intervals. An analysis of monetary policy based upon these variables would be a useful robustness check on our results. Fourth, since the exchange rate depends upon the domestic money supply *relative* to foreign money supply, the Fed may be signalling changes in relative monetary policy. While this paper has focused upon domestic money supply alone, the essential variables signalled by intervention may be the relative tightness of U.S. policy relative to its trading partners.

Overall, this paper represents an important first attempt at testing whether and how intervention interacts with future shifts in money supply. As such, it also points to a new direction for research on the potential effectiveness of foreign exchange intervention.

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APPENDIX

Estimation Procedure of the Markov–Switching Model without Intervention as a Signal

The switching regime model in Section IV is estimated under the assumption that traders do not observe the monetary regime, which must be inferred based on the observation of current and past values of the monetary indicator ($\phi_t=\{\Delta x_t,\Delta x_{t-1},\ldots,\Delta x_1\}$). The optimal forecast of this process can be thought as the following sequence of steps. For any period t, traders have a certain prior about the probability of being in Regime 1 based on past information.

(A1) $$\text{Prior}(R_t=1) = (1-\lambda)\text{Post}(R_{t-1}=1)+\lambda[1-\text{Post}(R_{t-1}=1)]$$

where $\text{Prior}(R_t=1)=\text{Prob}(R_t=1|\Delta x_{t-1},\ldots,\Delta x_1)$, $\text{Post}(R_t=1)=\text{Prob}(R_t=1|\Delta x_t,\ldots,\Delta x_1)$. They observe new information on monetary policy and they calculate the density function of Δx_t

(A2) $$f(\Delta x_t|\Delta x_{t-1},\ldots,\Delta x_1) = f(\Delta x_t|R_t=1)\text{Prior}(R_t=1)+f(\Delta x_t|R_t=0)[1-\text{Prior}(R_t=1)]$$

where $f(\Delta x_t|R_t=i)=((1/2)\pi\sigma^2)^{-1/2}\exp(-1/2(\Delta x_t-\delta_i^0-\sum_{j=1}^{s}\delta_j^i\Delta x_{t-j})^2/\sigma^2)$. Finally, they update their predictions using Bayes formula:

(A3) $$\text{Post}(R_t=1) = \frac{f(\Delta x_t|R_t=1)\text{Prior}(R_t=1)}{f(\Delta x_t|\Delta x_{t-1},\ldots\ldots,\Delta x_1)}.$$

They update repeatedly over the entire sample using (A1)-(A3).

The estimation procedure is simple enough. Start at t=1 with a prior about being in Regime 1. Using (A1)–(A3), construct the sample log likelihood function

(A4) $$\ln f(\Delta x_t,\Delta x_{t-1},\ldots,\Delta x_1) = \sum_{t=1}^{T} \ln f(\Delta x_t|\Delta x_{t-1},\ldots,\Delta x_1)$$

which can be maximized numerically with respect to the unknown parameters δ_0^0, δ_0^1, δ_j^0,

δ_j^1, σ, and λ.

Estimation Procedure of the Markov–Switching Model with Intervention as a Signal

The switching regime model in Section V is also estimated under the assumption that traders do not observe the monetary regime, which must be inferred based on the observation of current and past values of the monetary indicator and the intervention signal ($\phi_t = \{\Delta x_t, S_t, I_{t-k}, \ldots, \Delta x_1, S_1, I_{1-k}\}$). To learn about the monetary regime and about the information content of intervention in the foreign exchange market, rational investors follow a Bayesian strategy. Each period they start with a prior about the monetary regime and about the informational regime:

$$\text{(A5)} \qquad \text{Prior}(R_t=1) = (1-2\lambda)\text{Post}(R_{t-1}=1) + \lambda$$

$$\text{(A6)} \qquad \text{Prior}(C_t) = \{0\}^{(1-S_t)}\{(1-2p)\text{Post}(C_{t-1}) + p\}^{S_{t-1}}[q]^{(1-S_{t-1})}\}^{S_t}$$

where $\text{Post}(C_t)=\text{Prob}(C_t|\phi_t)$ and $\text{Post}(R_t=i)=\text{Prob}(R_t=i|\phi_t)$. Every period investors obtain more information on monetary policy and foreign exchange intervention and estimate the joint density function of Δx_t, S_t, and I_{t-k}

$$\text{(A7)} \qquad f(\Delta x_t, S_t, I_{t-k}|\phi_{t-1}) = [f(\Delta x_t|\phi_{t-1})]^{(1-S_t)}[f(\Delta x_t, I_{t-k}|\phi_{t-1})]^{S_t}$$

In (A7), when there is no signal, $S_t=0$, the model collapses to the Hamilton (1988) model. In this case $f(\Delta x_t|\phi_{t-1})$ is the marginal density of the monetary indicator and it is described in equation (A8). When there is a signal, $S_t=1$, the model collapses to the Kaminsky (1991) signalling model. In this case $f(\Delta x_t, I_{t-k}|\phi_{t-1})$ is the joint density of the intervention signal and the monetary indicator. This joint density function is depicted in (A9).

$$\text{(A8)} \qquad f(\Delta x_t|\phi_{t-1}) = f(\Delta x_t|R_t=1)\text{Prior}(R_t=1)+f(\Delta x_t|R_t=0)[1-\text{Prior}(R_t=1)]$$

$$\text{(A9)}\quad f(\Delta x_t, I_{t-k}/\phi_{t-1}) = \{[[f(\Delta x_t|R_t{=}1)\text{Prior}(C_t) - f(\Delta x_t|R_t{=}0)(1-\text{Prior}(C_t))] \times \text{Prior}(R_t{=}1) + f(\Delta x_t|R_t{=}0)(1-\text{Prior}(C_t))\}^{I_{t-k}} \times \{[[f(\Delta x_t|R_t{=}1)(1-\text{Prior}(C_t)) - f(\Delta x_t|R_t{=}0)\text{Prior}(C_t)] \times \text{Prior}(R_t{=}1) + f(\Delta x_t|R_t{=}0)\text{Prior}(C_t)\}^{1-I_{t-k}}$$

where $f(\Delta x_t|R_t{=}i) = ((1/2)\pi\sigma^2)^{-1/2}\exp(-1/2(\Delta x_t - \delta_i^0 - \sum_{j=1}^{S}\delta_j^i\Delta x_{t-j})^2/\sigma^2)$. This new information is used to update investors' priors:

$$\text{(A10)}\quad \text{Post}(R_t{=}1) = [\text{Post}(R_t{=}1|S_t{=}1)]^{S_t}[\text{Post}(R_t{=}1|S_t{=}0)]^{(1-S_t)}$$

$$\text{(A11)}\quad \text{Post}(C_t) = [0]^{(1-S_t)}[\text{Post}(C_t|S_t{=}1)]^{S_t}$$

where $\text{Post}(R_t{=}1|S_t{=}1)$, $\text{Post}(R_t{=}1|S_t{=}0)$, and $\text{Post}(C_t|S_t{=}1)$ are defined in equations (A12)–(A14).

$$\text{(A12)}\quad \text{Post}(R_t{=}1|S_t{=}0) = \frac{f(\Delta x_t|R_t{=}1)\text{Prior}(R_t{=}1)}{f(\Delta x_t|\phi_{t-1})}$$

$$\text{(A13)}\quad \text{Post}(R_t{=}1|S_t{=}1) = \frac{f(\Delta x_t|R_t{=}1)\text{Prior}(R_t{=}1)\text{Prior}(C_t)^{I_{t-k}}(1-\text{Prior}(C_t))^{1-I_{t-k}}}{f(\Delta x_t, I_{t-k}|\phi_{t-1})}$$

$$\text{(A14)}\quad \text{Post}(C_t|S_t{=}1) = \text{Prior}(C_t)\frac{[f_1(\Delta x_t)\text{Prior}(R_t{=}1)]^{I_{t-k}}[f_0(\Delta x_t)\text{Prior}(R_t{=}0)]^{1-I_{t-k}}}{f(\Delta x_t, I_{t-k}|\phi_{t-1})}$$

where $f_i(\Delta x_t) = f(\Delta x_t|R_t{=}i)$. The above model can be estimated as follows. Start at $t{=}1$ with a prior of being in Regime 1 and of being in a "Correct Signals" regime. Using (A5)–(A14), construct the sample log likelihood

$$\text{(A15)}\quad \ln(f(\Delta x_t, S_t, I_{t-k}, \ldots, \Delta x_1, S_1, I_{1-k})) = \sum_{t=1}^{T}\ln(f(\Delta x_t, S_t, I_{t-k}|\phi_{t-1}))$$

which can be maximized numerically with respect to the unknown parameters δ_0^0, δ_0^1, δ_j^0,

δ_j^1, σ^2, λ, p, and q.

TABLE 1

MONETARY AND INTERVENTION POLICY
Summary Information

Period	Intervention total	S	B	Δm (annual rate)	CHANGES IN THE DISCOUNT RATE
09/23/85 to 12/31/85	10	10	0	7.97%	
01/01/86 to 06/30/86	–2	0	–2	14.17%	–0.50% April
07/01/86 to 12/31/86	0	0	0	24.09%	–1.00% August
01/01/87 to 06/30/87	–6	3	–9	1.57%	
07/01/87 to 12/31/87	–9	4	–13	2.85%	+0.50% October
01/01/88 to 06/30/88	–15	1	–16	7.56%	
07/01/88 to 12/31/88	11	22	–11	1.67%	+0.50% August
01/01/89 to 06/30/89	54	54	0	–3.50%	+0.50% February
07/01/89 to 12/31/89	28	28	0	6.67%	
01/01/90 to 02/02/90	7	7	0	–5.22%	

Notes: S: Number of days of Intervention selling dollars (+), B: Number of days of Intervention buying dollars (–).
Δm = growth rate of M1.

Table 2

Markov Switching Model for M1 and the Federal Funds Rate

$$\Delta x_t = \delta_0^i + \sum_{m=1}^{s} \delta_m^i \Delta x_{t-m} + \epsilon_t \quad \text{for } R_t = i,\ i = 0,1$$

$$\text{Prob}(R_t = j \mid R_{t-1} = i) = \lambda$$

Parameter	δ_0^0	δ_1^0	δ_0^1	δ_1^1	λ	σ
			Money Supply (M1)			
Estimate	0.0479		0.3324		0.9425	0.3293
Standard Error	0.0265		0.0740		0.8434	0.0162
t–Statistic	1.8087		4.4689		1.1176	20.3250
			Federal Funds Rate			
Estimate	0.0351	−0.2599	−0.0442	−0.4795	1.2934	0.1854
Standard Error	0.0252	0.1131	0.0211	0.1050	1.2444	0.1854
t–Statistic	1.3891	−2.2971	−2.0949	−4.5677	1.0397	1.0397

Notes: When the monetary indicator is money supply δ_0^0 and δ_1^1 are in percent. λ is also in percent.

TABLE 3

Regime Switching Model for M1 and the Federal Funds Rate with Intervention as a Signal

$$\Delta x_t = \delta_0^i + \sum_{m=1}^{s} \delta_m^i \Delta x_{t-m} + \epsilon_t, \text{ for } R_t = i,\ i = 0,1$$

$$\lambda = \mathrm{Prob}(R_t = j \mid R_{t-1} = i)$$

$$p = \mathrm{Prob}(C_t \mid S_t = 1, S_{t-1} = 1, W_{t-1}) = \mathrm{Prob}(W_t \mid S_t = 1, S_{t-1} = 1, C_{t-1}),\ q = \mathrm{Prob}(C_t \mid S_t = 1, S_{t-1} = 0)$$

Parameter	δ_0^0	δ_1^0	δ_0^1	δ_1^1	λ	p	q	σ
				Money Supply (M1) LRT=64.329 (0.000)(a)				
Estimate	0.058		0.373		0.570	2.139	42.315	0.329
Standard Error	0.025		0.045		0.432	1.770	8.428	0.015
t–Statistic	2.334		8.377		1.317	1.210	5.021	21.541
				Federal Funds Rate LRT=67.871 (0.000)(a)				
Estimate	0.017	–0.203	–0.023	–0.497	0.423	0.000	30.216	0.187
Standard Error	0.016	0.086	0.019	0.086	0.389	6.217	7.847	0.009
t–Statistic	1.035	–2.349	–1.288	–5.749	1.086	0.000	3.851	21.244

Notes: When the monetary indicator is money supply δ_0^0 and δ_1^1 are in percent. λ, p, and q are also in percent. LRT is the likelihood ratio test of the null hypothesis that intervention does not convey any information about monetary policy.
(a) marginal significance level.

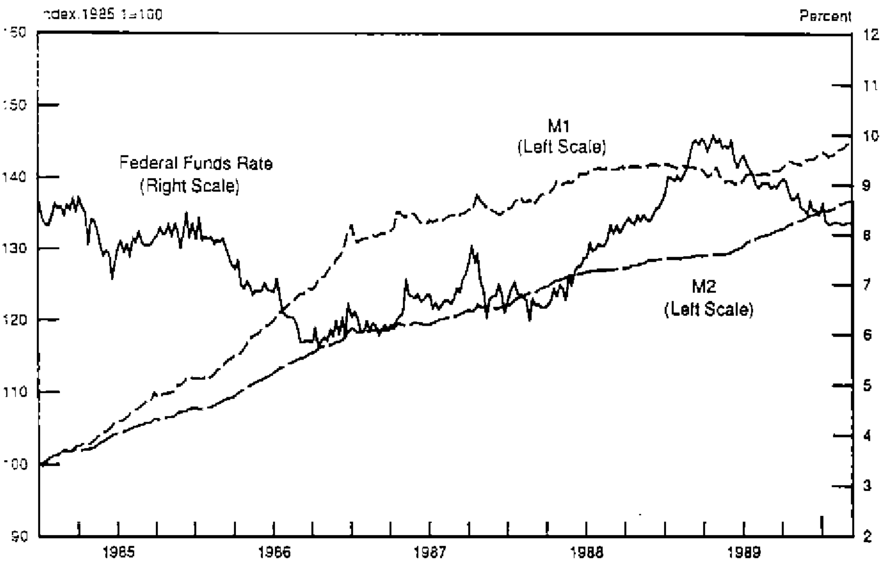
Table 4

Exchange Rates Changes and Foreign Exchange Intervention

Period	Currency	Reaction of Exchange Rates to Intervention							
		Days of Selling Dollars Intervention				Days of Buying Dollars Intervention			
		Correct Signals		Wrong Signals		Correct Signals		Wrong Signals	
		Mean	t–Stat.	Mean	t–Stat.	Mean	t–Stat.	Mean	t–Stat.
09/23/85–12/31/85	DM	–1.097	–4.968	0.152	0.584				
	JY	–1.058	–11.231	0.106	0.400				
01/01/87–12/31/87	DM	0.001	0.006	0.534	1.557	–0.173	–1.585	–0.510	–3.384
	JY	–0.114	–1.209	0.430	2.127	–0.220	–1.331	–0.744	–3.985
01/011/88–12/31/88	DM			0.376	2.217	0.111	0.443	–0.272	–1.343
	JY			0.260	2.170	0.259	2.170	–0.190	–1.343
01/01/89–02/02/90	DM			0.201	2.659				
	JY			0.238	2.917				

Notes: Reaction is the percentage change the exchange rate on the day of the intervention relative to the exchange rate on the previous day. Rates are quoted at 12 noon New York market. DM: Deutsche mark/dollar rate, JY: Japanese yen/dollar rate. The "Correct Signals" and "Wrong Signals" episodes are obtained from the Signalling model in Section V using the Federal Funds rate as the monetary indicator.

Figure 1:
Relationship Between Monetary Variables



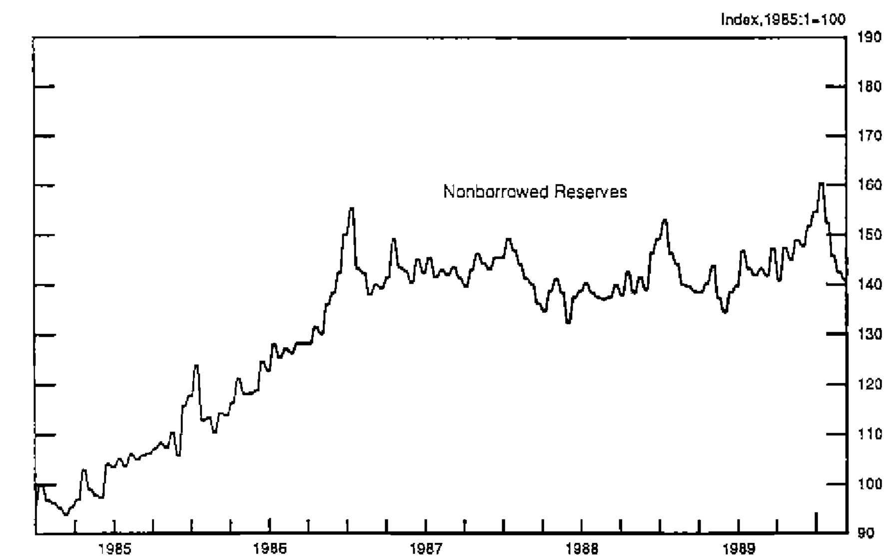
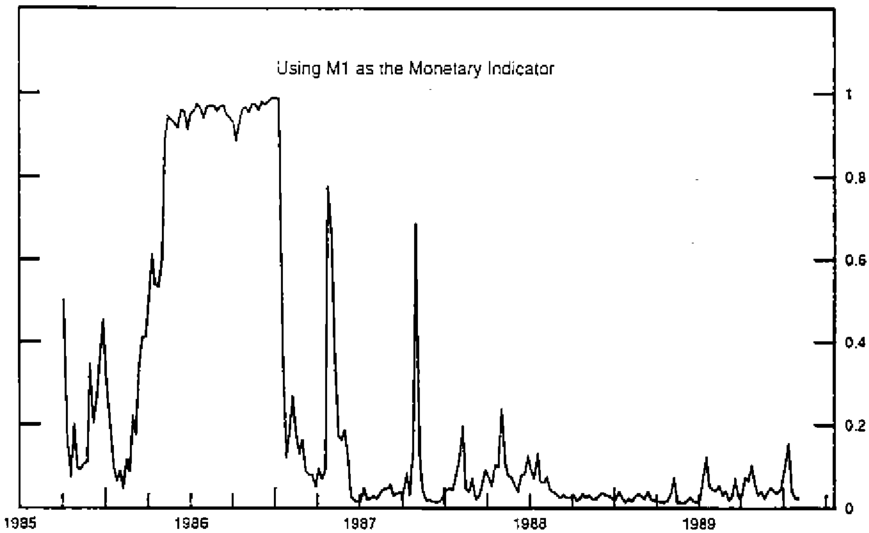


Figure 2: Prior Probabilities of an Expansionary Monetary Regime
(Without Using Intervention Signals)



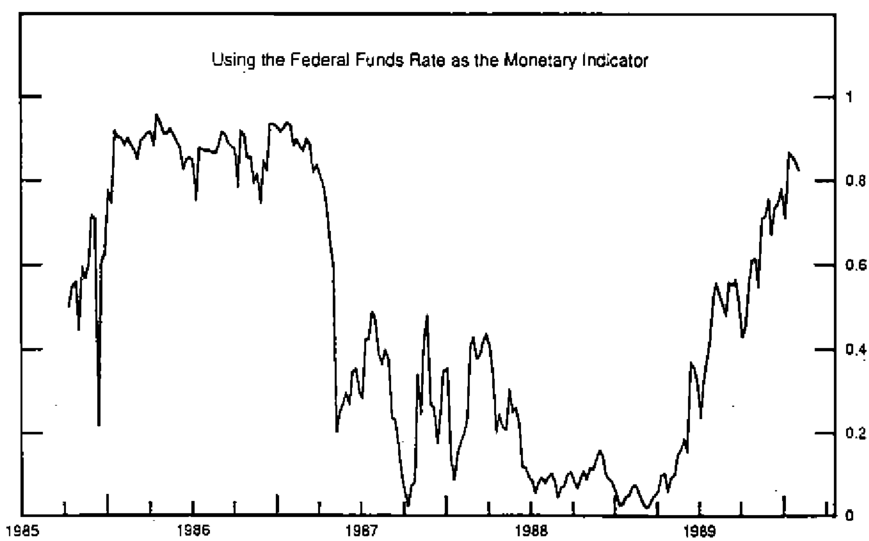
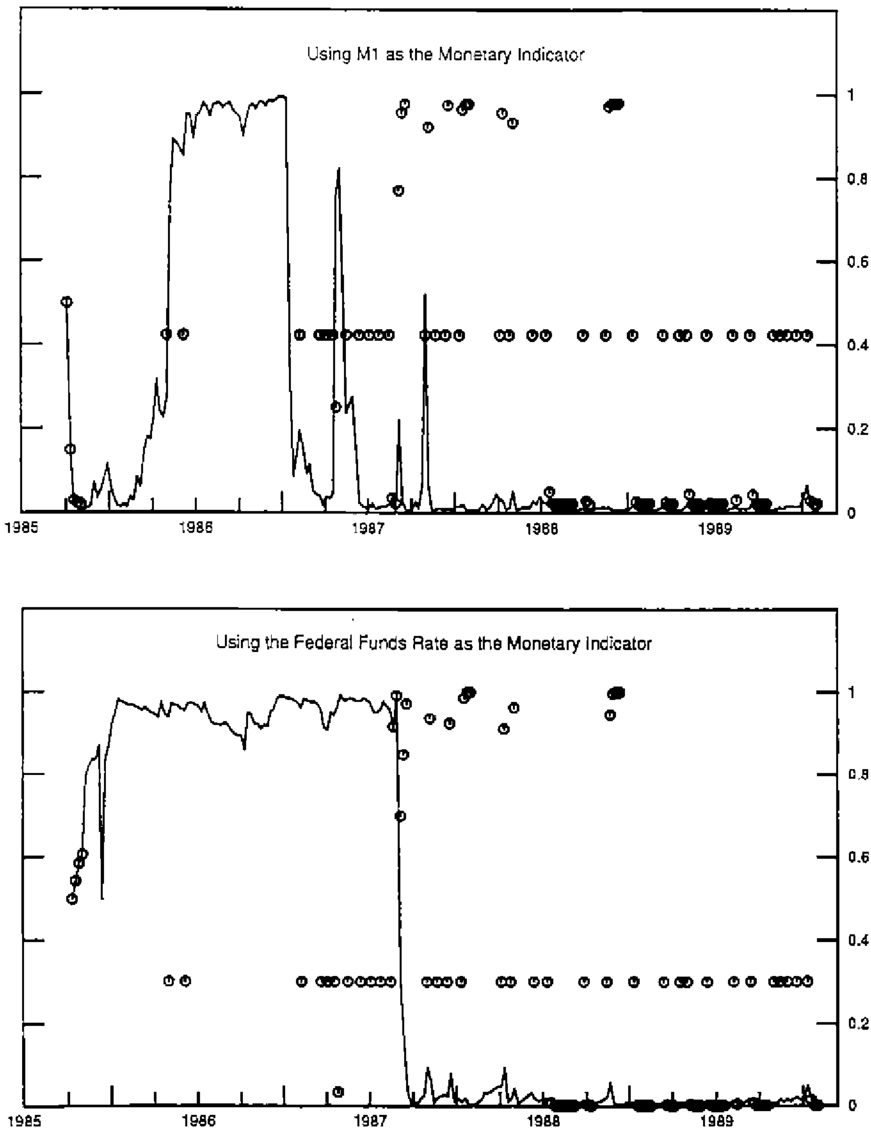


Figure 3:
Prior Probabilities Implied by the Signalling Model



— Probability of an Expansionary Monetary Regime
-o- Probability of a "Correct Signals" Regime

Figure 4:
Posterior Probabilities Implied by the Signalling Model