Day-To-Day Monetary Policy and the Volatility of the Federal Funds Interest Rate

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Abstract[1]

We propose a model of the interbank money market with an explicit role for central bank intervention and periodic reserve requirements, and study the interaction of profit-maximizing banks with a central bank targeting interest rates at high-frequency. The model yields predictions on biweekly patterns of the federal funds rate's volatility and on its response to changes in target rates and in intervention procedures, such as those implemented by the Fed in 1994. Theoretical results are consistent with empirical patterns of interest rate volatility in the U.S. market for federal funds.

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1. Introduction

In the federal funds market U.S. banks exchange unsecured loans of non-interest-bearing reserves, whose supply the Fed controls daily by intervention. Despite this market's role as the channel for implementation of U.S. monetary policy, the details of the transmission of Fed actions to federal funds interest rates have received scant attention in previous research. At one end of the spectrum, a body of work has studied the behavior of money markets focusing on their micro-structure and on interbank relationships, but abstracting from the effects of monetary policy on liquidity and interest rates (for instance, Ho and Saunders, 1985, Kopecky and Tucker, 1993, and Hamilton, 1996). At the opposite end, textbook monetary theory and models of money markets, such as Campbell (1987) and Coleman et al. (1996), have sidestepped the analysis of interbank relationships, of the microeconomics of banks' demand for money, and of institutional details that constrain daily Fed operations and banks' liquidity management.

This paper partially bridges the gap between these two lines of research. We model banks' liquidity management and official intervention policies jointly, in a setting which accounts explicitly for the main institutional features of the U.S. federal funds market. The model suggests that the volatility of equilibrium interest rates within reserve maintenance periods depend on the market's perception of the likelihood and size of future Fed intervention. We show that this perspective can explain important features of the empirical behavior of the federal funds rate's volatility, including its biweekly patterns and its response to changes in intervention procedures, such as those implemented by the Fed in 1994.

High-frequency patterns of federal funds rate volatility are especially intriguing in light of the Fed's effort to target interest rates. In this respect, one of our goals is to explain how such patterns can survive the Fed's attempt to keep rates close to target and their volatility in check. More practically, our interest in federal funds rate volatility reflects the concern displayed towards it by both financial institutions and the Fed. For banks, failure to adjust reserves in response to daily rate changes would have direct impact on their balance sheets and profitability. The Fed, in turn, has traditionally been concerned with short-term interest volatility, fearing it might hinder banks' operations "and lead market participants to make bad decisions" (Dumitru and Stevens, 1991). The Fed's Open Market Desk may also be concerned that, over time, large deviations of the federal funds rate from its target may dilute the credibility of its mandate, especially if daily changes in market rates exceed typical quarter-percent Fed target changes.

Whether or not these concerns are justified from a macroeconomic viewpoint, they have motivated operational and institutional changes. For instance, between 1997 and 1999, the Fed shifted its intervention from 11:30 to 9:30 a.m., to allay problems of thinness in the repo market which could limit its ability to inject the desired amount of reserves. In 1998 the Fed reinstated the system of lagged reserve requirements it had abandoned in 1984, so as to reduce uncertainty on required reserves. Most notably, in 1994 the Fed began to announce changes in target rates, implementing them mainly at times of FOMC meetings, presumably to reduce uncertainty on its policy stance and the market volatility associated with it. These changes motivate us to study how the Fed's intervention style affects interest volatility and its response to changes in intervention procedures.[2]

The closest antecedent of our research is Hamilton (1996), who offers a comprehensive analysis of the federal funds market and a model that explains the periodic patterns in mean overnight rates documented by Campbell (1987), Lasser (1992), Rudebusch (1995), Roberds et al. (1996), Balduzzi et al. (1997), among others, and by Hamilton's own work. Because it abstracts from aggregate uncertainty and official intervention, however, Hamilton's model cannot tackle issues related to interest rate volatility, nor can it explain how interest rate patterns can survive the Fed's targeting effort, or the tendency of short-term rates to hover around official targets and quickly revert to them in response to shocks. For this reason, unlike other studies such as Spindt and Hoffmeister (1988) and Griffiths and Winters (1995), we model explicitly the Fed's effort to target rates. In our model, banks minimize the opportunity cost of reserve requirements by trading in the interbank market in response to both exogenous *and* intervention-induced shocks to liquidity. For simplicity, we abstract from market imperfections such as lines of credit, transaction costs, and bid-ask spreads. The resulting model lets the Fed achieve its target on average each day, but generates rich patterns of volatility which, our model suggests, reflect the Fed's intervention procedures and--in particular--its ability (or willingness) to fully offset high-frequency liquidity shocks.

Bringing our theoretical perspective to the data, we adopt a time-series methodology which builds on Rudebusch (1995), Hamilton (1996), and Balduzzi et al. (1997). Analysis of twelve years of federal funds data confirms the model's main predictions, in particular: that the volatility of interest rates begins to rise in advance of reserve-settlement days; that it has declined in "high-rate" regimes (i.e., when the Fed's target rate has approached the penalty rate on reserve deficiencies); and that its biweekly periodicity has become less marked when banks could hold greater confidence in the Fed's commitment to keep rates close to their target.

2. A model of the federal funds market with Fed intervention

2.1. The model. In discrete time, we consider a market populated by risk-neutral, atomistic banks with unit total mass, subject to reserve requirements. We focus on the behavior of the overnight interbank ("federal funds") rate, r_t, over a "maintenance period" with T days. With no qualitative loss of generality, we set reserve requirements at zero. Denoting bank i's reserves at the end of day t by x_{it}, and end-day average reserves by $a_{it}=(x_{i1}+\ldots+x_{it})/t$, reserve requirements are expressed by $a_{iT}\geq 0$. To focus on the effect of periodic requirements on interest rates, we abstract from other regulations such as overnight or intraday penalties on reserve deficiencies.

The model's daily time line, summarized in Table 1, captures the main qualitative features of the Fed's intervention procedure (see Goodfriend, 1991). At the beginning of each day (shortly after 9:30 a.m., in New York) the Fed provides an amount m_t of aggregate reserves ("federal funds"), aiming to keep the expected interbank overnight rate as close as possible to the target r^*. Intervention is recorded as a change in banks' account at the Fed.

Every day, shortly after the Fed's intervention, a random zero-mean shock ν_t alters banks' stock of reserves. This shock's real-life counterpart is a within-day Fed forecast error of Treasury payments and other flows from the non-bank sector. After the realization of ν_t, each bank may borrow or lend overnight an amount b_{it} of unsecured funds in the interbank market. As in the classic Poole (1968) model, we let all such interbank transactions occur simultaneously at a single market-clearing rate r_t. After the market has cleared a second (zero-mean) liquidity shock ϵ_t is realized, and bank i's average reserve position to date is tallied as:

$$a_{it}=\tilde{a}_{it}+(b_{it}+\epsilon_t)/t \quad =\big((t-1)a_{i,t-1}+m_t+\nu_t+b_{it}+\epsilon_t\big)/t\ , \tag{1}$$

where $\tilde{a}_{it}$ is the bank's average reserve position just before market-opening on day t. (The subscript i is omitted for industry-wide variables.) This routine is repeated each day $t=1,\ldots,T$ of the maintenance period. At the end of the last ("settlement") day T of the period, a penalty rate $\bar{r}$ is charged on cumulated reserve deficiencies, so that bank *i* pays $-\min\{\bar{r}\, Ta_{iT}, 0\}$.

2.2. Equilibrium and targeting on settlement day. We now study the equilibrium federal funds rate $r_t(\tilde{a}_t)$, as a function of the industry's reserve position $\tilde{a}_t$ each day at market-opening.

We solve the model moving backwards in time over the maintenance period. When the market opens on day *T*, bank *i* borrows or lends at the (market-clearing) rate r_T so as to optimally trade-off the expected cost of reserve shortfalls against the opportunity cost of carrying on its books non-interest-bearing reserves rather than loans. Before penalties are assessed, both the amount borrowed (lent, if negative) b_{iT} and the yet-to-be realized shock ϵ_T will be added to average reserves $\tilde{a}_{iT} = \left((T-1)a_{i,T-1} + m_T + \nu_T\right)/T$. Hence, bank *i*'s problem is:

$$\max_{b_{iT}} V_{iT} = \bar{r} \int_{-\infty}^{-T\tilde{a}_{iT} - b_{iT}} \left[T\tilde{a}_{i,T} + b_{iT} + \epsilon_T\right] dF(\epsilon_T) - r_T b_{iT}, \tag{2}$$

where $F(.)$ is the cumulative distribution function of ϵ_t, assumed increasing over its support, and $F^{-1}(.)$ is its inverse. The optimal b_{iT}^* uniquely satisfies the first-order condition for (2):

$$F\left(-T\tilde{a}_{iT} - b_{iT}^*\right) = \frac{r_T}{\bar{r}}, \tag{3}$$

or, after inverting $F(.)$:

$$b_{i,T}^*(\tilde{a}_{i,T}, r_T) = -T\tilde{a}_{i,T} - F^{-1}\left(\frac{r_T}{\bar{r}}\right). \tag{4}$$

Intuitively, b_{iT}^* rises with $\bar{r}$ and falls with both r_T and the inherited reserve position $\tilde{a}_{iT}$.

While each bank views itself as able to trade arbitrary amounts at r_T, the market must clear with zero net borrowing. We sum (4) over banks' unitary measure, impose zero total net borrowing (so that $\tilde{a}_T = \tilde{a}_{iT}$ and $b_{iT}^* = b_T^* = 0$), and invert $F^{-1}(.)$. The resulting market-clearing rate,

$$r_T(\tilde{a}_T) = \bar{r}\, F(-T\tilde{a}_T), \tag{5}$$

is a probability-weighted average of the possible marginal value of funds *after* the realization of

ϵ_T: the penalty rate $\bar{r}$, and zero (the value of unremunerated excess reserves). The weight attached to $\bar{r}$ is the probability of a reserve deficiency, which falls with the inherited position $\tilde{a}_T$.

Consider next the Fed's problem of choosing, earlier on day *T*, how much liquidity to inject into (or drain from) the market. To minimize the expected deviation of the equilibrium rate (5) from its target r^*, the size of the Fed's liquidity injection m_T must be such that:

$$\bar{r}\,\mathrm{E}\Big[F\big(-(T-1)a_{T-1} - m_T - \nu_T\big)\Big] = r^*, \tag{6}$$

where the expectation is taken with respect to the distribution of the shock ν_T realized between the Fed's intervention and market clearing.

2.3. Non-settlement days equilibrium. A no-arbitrage relationship similar to that valid on day *T* holds also on previous days. Each day, banks hold reserves only if their opportunity cost (the overnight rate r_t) equals the expected discounted penalty on reserve deficiencies at *T*. Otherwise, banks would try to meet requirements--thus bidding up rates--on days with relatively low rates, and vice versa. Hence, as noted by Campbell (1987) and others, the equilibrium rate must be expected to remain constant within each maintenance period, i.e., it must behave as a martingale.

The previous point is made more formally as a standard variational argument. For interest rates to be in equilibrium, a bank should not expect to profit by borrowing one less dollar at *t* and one more dollar at *t*+1: the expected loss from this perturbation, $r_t - \mathrm{E}_t\big[r_{t+1}\big]/(1+r_t)$, should equal zero. As discounting is negligible for realistic values of r_t, we write

$$r_t \;=\; \mathrm{E}_t\big[r_{t+1}\big] \;=\; \mathrm{E}_t\big[r_T\big] \tag{7}$$

within each maintenance period.

Earlier contributions, and our own work in Section 4, document that the martingale property (7) is violated by U.S. federal funds rate data. The small, but statistically significant violations of (7) observed in reality may be rationalized by transaction costs, interbank credit limits, overdraft penalties, and other obstacles to intra-period arbitrage. The volatility patterns we analyze in this paper, however, arise even when (7) holds, and reflect the interaction of banks' optimizing behavior with the Fed's intervention procedures. To illustrate this point, we first proceed to characterize two polar cases: that of no official intervention ($m_t \equiv 0$ for all t), and that where the Fed intervenes so as to achieve the target rate r^* as exactly as possible.

2.4. Interest rates and liquidity without intervention. Consider first how interest rate volatility would evolve in the absence of Fed intervention. In this case, the dynamics of r_t reflect banks' daily update of forecasts of their day-T reserve position, a_T. From (7) and (5), the equilibrium rate on day t is:

$$r_t = \mathrm{E}_t\left[r_T\right] = \bar{r}\,\mathrm{E}_t\left[F\left(-T\tilde{a}_T\right)\right]. \tag{8}$$

Since $\tilde{a}_T = \frac{t}{T}\tilde{a}_t + \frac{1}{T}\sum_{i=t}^{T-1}(\epsilon_i + \nu_{i+1})$, and $\sum_{i=t}^{T-1}(\epsilon_i + \nu_{i+1})$ is random as of market-clearing time on day t, (8) defines the equilibrium interest rate for day t as a price/quantity schedule $r_t = r_t(\tilde{a}_t)$. The shape and position of this schedule depend on the probability distribution of further shocks during the period. A tractable case is that with independent and identically distributed normal shocks (as in Angeloni and Prati, 1996), with $\nu_t \sim \mathrm{N}(0, \sigma_\nu^2)$ and $\epsilon_t \sim \mathrm{N}(0, \sigma_\epsilon^2)$. The rate realized on day T is then $r_T = \bar{r}\Phi(-T\tilde{a}_T/\sigma_\epsilon)$, where $\Phi(.)$ is the cumulative standard normal distribution. Equilibrium rates on earlier days can then be computed from (8), since:

$$T\tilde{a}_T = t\tilde{a}_t + \sum_{i=t}^{T-1}(\epsilon_i + \nu_{i+1}) \sim \mathrm{N}\left(t\tilde{a}_t, (T-t)(\sigma_\epsilon^2 + \sigma_\nu^2)\right), \tag{9}$$

given information at market-clearing time on day t, so that:[3]

$$r_t = \bar{r}E(\Phi(-T\tilde{a}_T/\sigma_\epsilon) = \bar{r}\,\Phi\left(\frac{-t\tilde{a}_t}{\sqrt{(T-t)\sigma_\nu^2 + (T-t+1)\sigma_\epsilon^2}}\right). \tag{10}$$

Figure 1 plots (10) as a function of $\tilde{a}_t$, for each t. Higher reserves lower the likelihood of penalties on reserve deficiencies, hence are associated with lower equilibrium rates. Also, the slope of this relationship rises as t goes to T: uncertainty about reserves on day T is gradually resolved, so that the current reserve position becomes more and more precise as a signal of eventual reserve shortfalls.

Equation (8) has also implications for the variability of r_t *across* and *within* maintenance periods. Since the unconditional mean of r_t is $\bar{r}/2$ and $t\tilde{a}_t = \sum_{i=1}^{t-1}(\epsilon_i+\nu_i)+\nu_t \sim N(0, t\sigma_\nu^2+(t-1)\sigma_\epsilon^2)$, denoting $t\tilde{a}_t = x$, and using (10), the unconditional variance of interest rate levels is:

$$\operatorname{var}(r_t) = E\left[(r_t)^2\right]-\left(E[r_t]\right)^2 = \int_{-\infty}^{\infty}\left[\bar{r}\,\Phi\left(\frac{-x}{\sqrt{(T-t)\sigma_\nu^2+(T-t+1)\sigma_\epsilon^2}}\right)\right]^2 \phi\left(\frac{x}{\sqrt{t\sigma_\nu^2+(t-1)\sigma_\epsilon^2}}\right)\mathrm{d}x - \left(\frac{\bar{r}}{2}\right)^2. \qquad (11)$$

The variance of r_t rises through each period, irrespective of distributional assumptions. Since all interest rates in each maintenance period rationally forecast r_T, and information on r_T accruing between t-1 and t is uncorrelated with that available at t-1, $\operatorname{cov}(r_t-r_{t-1}, r_{t-1})=0$ and $\operatorname{var}(r_t) \equiv \operatorname{var}(r_t-r_{t-1}+r_{t-1}) = \operatorname{var}(r_t-r_{t-1}) + \operatorname{var}(r_{t-1}) > \operatorname{var}(r_{t-1})$. By the same martingale property, $\operatorname{var}(r_t-r_{t-1}) = \operatorname{var}(r_t) - \operatorname{var}(r_{t-1})$; hence the variance of interest rate *changes* is readily computed by evaluating (11) at t and t-1. Increasing sensitivity of equilibrium rates to reserve levels also yields increasing average volatility of interest rates. In fact, changes in $\tilde{a}_t$ contain little information on likely changes in $\tilde{a}_T$ when t is small. Hence, shocks occurring early in each period cause only small changes in interest rates, while later liquidity shocks generate relatively higher volatility of interest rate changes.

2.5. The role of official targeting. The opposite case to that of Section 2.4 is that where the

Fed defends a known target r^* on day T. To capture this role of the Fed, we extend our analysis of Section 2.1 and suppose that the Fed intervenes each day to provide just enough liquidity for banks to trade, on average, at r^*. That is, the Fed chooses m_t so that:

$$\mathrm{E}_{t-1}\left[r_t(\tilde{a}_t) \right] = \mathrm{E}_{t-1}\left[r_t((t-1)a_{t-1} + m_t + \nu_t) \right] = r^* . \tag{12}$$

Then, by (7), $r_t = \mathrm{E}_t[r_T] = r^*$ for $t = 1, \ldots, T-1$: through day T-1, banks would only trade at r^*, irrespective of their reserve position, since this is the rate expected to prevail on day T (see Figure 2). Hence, the martingale process followed by equilibrium rates has no innovations, the reverse-S shaped schedules of Figure 1 become flat at r^* for $t = 1, \ldots, T-1$, and neither the interest rate's level, nor its daily change, display any volatility through day T-1.

On day T, however, the Fed intervenes before ν_T is realized. Hence, on this day, the equilibrium rate generally differs from r^*, and interest rate volatility is positive. This is the case whether the Fed offsets liquidity shocks daily, or postpones intervention to future days, possibly by engaging in a once-for-all operation at T: even if shocks are not offset daily, banks use their reserve account as a buffer, counting on the Fed's offsetting action on day T or sooner.

3. Models of imperfect day-to-day targeting

Unsurprisingly, the volatility pattern of U.S. data displayed in Figure 3 is not well approximated by the predictions of the two extreme cases just discussed. The idea that the funds rate should be less volatile in the early portion of the maintenance period captures important features of the market. As shown in Figure 3 (see, in particular, the plots of outlier-robust statistics), federal funds rates are indeed much more stable in the first few days of each period, while their volatility is sharply higher on settlement days than on previous days.

However, in contrast with the case of Section 2.5, where the Fed achieves its target exactly on all non-settlement days, interest rate volatility is always positive and rises before settlement day. Clearly, banks do not expect the Fed to always provide liquidity perfectly elastically at the current target rate. This suggests that some of the features of the model without intervention of Section 2.4 need to be captured by a realistic model of the federal funds market.

In general, the Fed may accommodate liquidity shocks incompletely either because institutional features of the market limit its ability to intervene on any given day, or because it prefers to allow interest rate changes to absorb part of realized liquidity shocks. In practice, interest rate behavior is similar whenever the Fed partly accommodates liquidity shocks, regardless of whether it is *unable* or *unwilling* to supply funds elastically when the funds rate is not trading at the target. We discuss and model the former case in some detail, and outline the qualitative analogy with the latter at the end of this section.

The Fed has historically found it difficult to implement unusually large repurchase agreement (RP) operations, for reasons that both the Fed and market participants understand well. The Fed can undertake an RP only if its market counterparts have sufficient collateral (i.e., Treasury securities). While the banking system as a whole may acquire collateral by trading with non-bank customers, it cannot do so quickly: for purposes of very-short-term liquidity management, the collateral available in the system as a counterpart to the Fed's RPs is largely constrained by past decisions. Indeed, the market for Treasury securities is relatively thin around the traditional time of Fed intervention (Fleming, 1997, finds that late-morning volume averages only half of its 8:30 a.m. peak), a problem which the Fed recently tried to mitigate by shifting its intervention from 11:30 a.m to 9:30 a.m.

The Fed may also have faced difficulties when draining liquidity by "reverse RP" operations. These difficulties may have stemmed in part from the Fed's own procedures, including its former reluctance to extend discount credit to banks which had just undertaken a reverse.[4] Finally, even when these constraints were not binding, the Fed may have refrained from undertaking unusually large operations, to avoid having later to take opposite action in response to new information, a practice which--at least until 1994--the Fed felt could provide mixed signals of its policy stance. Overall, the size of Fed interventions may have been limited by such institutional features. However, these limits are likely to have become less significant in recent years, as we later discuss, leading to a natural test of one of our model's predictions.

A simple way to study the effects of limits on Fed intervention is to constrain m_t to the range $[-\bar{m}, \bar{m}]$. Absence of intervention (Section 2.4) is then encompassed as the special case with $\bar{m}=0$, and the case where the Fed fully offsets shocks (Section 2.5) as that with $\bar{m}\to\infty$.

Before discussing this model's solution, it should be intuitive why limits to intervention should imply a rise in volatility *before* period-end. The equilibrium interest rate depends on cumulative Fed intervention expected by day *T*. While "early" shocks can be offset by a series of small operations in each of the remaining days, the Fed's reaction to "late" shocks cannot be spread out and may require excessively large operations. Thus, late shocks provide more precise signals of the Fed's possible inability to hit its target, causing a stronger interest rate response.

To illustrate this insight, we consider a parameterized version of the model. We let the distribution of the shocks ν_t and ϵ_t be uniform, and solve the model backwards using the analytical solution for day *T* as a terminal condition. We discretize the functionals $r_T(\tilde{a}_T)$ and $m_T^*(a_{T-1})$ over grids for $\{\tilde{a}_T\}$ and $\{a_T\}$, and the functional $V_{iT}^*(\tilde{a}_{iT}, r_T(\tilde{a}_T))$ over a grid for $\{\tilde{a}_T, \tilde{a}_{iT}\}$. We compute $E_{T-1}\left[V_{i,T}^*\left(\tilde{a}_{i,T}, r_T(\tilde{a}_T)\right)\right]$, banks' expected value for period *T*, by taking expectations over ϵ_{T-1} and ν_T and interpolating, for each realization of ϵ_{T-1} and ν_T, from the grid values of $V^*_{iT}(\tilde{a}_{iT}, r_T(\tilde{a}_T))$. An iterative algorithm then solves for the unique arbitrage-free equilibrium rate at T-1. Given $r_{T-1}(\tilde{a}_{T-1})$, the Fed's targeting problem for day T-1 is then solved, conditional on a_{T-2}, by calculating m_{T-1} so that $\mathrm{E}_{T-1}\left[r_{T-1}(\tilde{a}_{T-1})\right] = r^*$. $m^*_{T-1}(a_{T-2})$ is then discretized over a grid for a_{T-2}, and so on, for $t = T-2, T-3, .., 1$.

Figure 4 illustrates the solution when $T=10$, $\bar{r}=0.04$, $r^*=0.02$, $\bar{m}=1.5$, and the standard deviations of the uniformly distributed shocks are $\sigma_\epsilon = 2$ and $\sigma_\nu = 0.2$ (thus assuming the Fed to have access to most of the information relevant to each day's equilibrium). In the upper panel of Figure 4, the steepest curve is that for day 10, and it has the linear form of the cumulative distribution function of a uniform random variable. The curves for days $t = 9, 8, \ldots, 1$ are progressively flatter: as discussed above, banks know that reserve imbalance carried on days closer to settlement day are more likely to translate into end-period imbalances of the same sign. Thus, for smaller values of t, market-clearing rates deviate less from the target rate in response to a change in $\tilde{a}_t$. The lower panel of Figure 4 plots the implied pattern of volatility of the interest rate's daily changes, calculated as sample statistics from a Monte Carlo simulation with 10,000 iterations. Note how the sharp dichotomy in volatility between the first T-1 days and settlement day of Section 2.5 gives way to a smoother, rising pattern of volatilities.

The model also predicts that changes in volatility patterns should be observed in response to changes in the Fed's operating procedures. To illustrate this point, Figure 5 plots variance profiles for two different limits to Fed intervention, $\bar{m} = 1.5$ and $\bar{m} = 3$, along with the extreme cases of sections 2.4 (no official intervention, $\bar{m} = 0$) and 2.5 (full accommodation, $\bar{m} = \infty$). Intuitively, a higher value of $\bar{m}$ (i.e., stronger commitment by the Fed to its target rate) implies a volatility pattern closer to that of Section 2.5 (where the volatility is clustered on day T and the volatility on day T itself is lower) than to that of Section 2.4 (where the volatility rises gradually through the period). Thus, the model predicts that higher confidence in the Fed's ability to achieve its target should lower the volatility of interest rates on settlement day, and flatten the volatility profile in the early portion of the maintenance period.

The historical evolution of the federal funds market and of the Fed's procedures suggest that such predictions may be tested on "early" and "late" samples of federal funds data. In recent years, specialized dealers have replaced banks in the Fed's RP auctions and have played an increasingly important role in the interbank market. These dealers hold larger stocks of Treasury securities and have little reason to be concerned with the Fed's retaliatory behavior at the discount window following a reverse. The Fed also feels that its recent shift to earlier intervention time has improved its ability to intervene. Finally, since it began to announce its target rates in February 1994, the Fed has had less reason to be concerned with large operations as confusing signals of its policy stance. In our stylized setting, these considerations would be captured by a wider range $\left[-\bar{m}, \bar{m}\right]$ for the more recent period than for the late-1980s' or early-1990s' period, leading to less marked biweekly periodicity of interest rate volatilities.

Figure 6 illustrates another prediction of our model by plotting interest rates and variance profiles for two different levels of the target rate r^*: a higher *level* of r^* (relative to $\bar{r}$) should be associated with a lower *volatility* of federal funds rates when the target is closer to the penalty rate than to zero (as is realistic, since the effective federal funds rate never fell below half the penalty rate in our sample). To see why, note that when interest rates are close to the penalty rate, responses to shocks are truncated by banks' arbitrage at the margin $\bar{r}$. Hence, as in the top panel of Figure 6, a higher target rate implies flatter demand curves around the target level of reserves. This implies a less elastic (hence, less volatile) response of interest rates to shocks, another prediction we test empirically below.

Before considering empirical evidence, however, we note an alternative channel for liquidity shocks to be partly absorbed through changes in market rates. If the Fed *changes its target* at least partially in response to shocks that also affect reserves (e.g., positive shocks to inflation, output, or money demand in general), then these shocks spill into higher market rates, just as they would if the Fed kept its target unchanged but was bound to the range $[\bar{m}, -\bar{m}]$. The working paper version of this research (available on request from the authors) presents a formal model along these lines and finds that, intuitively, its predictions are similar to those of the model studied above. For instance, the same implications as in the "no intervention" case of Section 2.4 are obtained when the Fed changes its target in response to *all* shocks, so that target rates passively follow market rates. The same implications as in the "full accommodation" case of Section 2.5 are obtained when the Fed *never* changes its target, so that the Fed offsets all liquidity shocks, to let banks continue trading on average at that fixed target. More realistic intermediate implications are obtained if the Fed changes its target rate infrequently, letting shocks be partly accommodated by changes in interest rates and partly by changes in aggregate liquidity. Thus, the model predicts that the more committed the Fed is to the current target rate, the closer the volatility pattern should be to that of Section 2.5 than to that of Section 2.4.

4. Time-series properties of the U.S. federal funds rate

4.1. Data and summary evidence. Our sample includes (business) daily data from January 1, 1986, to July 1, 1998, for a total of 3,139 observations. The data, provided by the Federal

Reserve Bank of New York, include effective (transaction-weighted) and target federal funds rates, and FOMC dates, which we drew from the *Federal Reserve Bulletin*. Our sample extends considerably beyond those of previous related studies. These typically include data through the early 1990s, thus preventing analysis of the procedural changes implemented by the Fed in 1994; and they rarely include data on target rates, which were not announced by the Fed until 1994 (exceptions include Rudebusch, 1995, Balduzzi et al., 1997, and Hamilton and Jorda, 1997). Occasionally, the Fed specified its target as a range (of about a quarter-percent-point in size), rather than as a point value. In these cases, we took the midpoint of the range as the target rate.

Inspection of the data revealed many daily changes in federal funds rates of half-percent (annualized) or more, as well as several large outliers. Time-persistence in the volatility of daily changes and systematic volatility patterns were also apparent, reflecting both maintenance-period and other calendar effects: settlement, end-year, and end-quarter days, and days preceding and following holidays, featured especially large interest rate changes. (See Figure 3, especially the substantial difference between raw and outlier-robust statistics reported therein.) This informal evidence suggests that hypothesis-testing should rely on a rich empirical model, allowing for special calendar effects, conditional heteroskedasticity, and other effects on both the mean and volatility of interest rates. Furthermore, if the biweekly periodicity of volatility reflects modalities of Fed intervention as our model predicts, then differences in the behavior of federal funds rates' volatility should be apparent by comparing data from the post-1994 regime with the pre-1994 regime, when target changes were not announced, were change frequently (roughly once every two maintenance periods), and the Fed's ability (or willingness) to implement large interventions was more limited.

4.2. The empirical model. Our model is similar to that of Hamilton (1996), from which it differs by including additional variables explaining level and variability of interest rates; by assuming a different probability distribution for the error term; by including a larger sample of data; and by considering tests of hypotheses (e.g., of structural change) suggested by our theoretical model. Our goal was to capture fairly accurately the behavior of the federal funds rate, including deviations from martingale behavior, even though our theoretical model only focuses on the main patterns in volatility that should be apparent in the data. This effort is complementary to Hamilton's, who identifies patterns in both the level and volatility of interest rates, but only analyzes theoretically the former in a model with deterministic interest rates.

Denoting by v_t a mean-zero, unit variance, i.i.d. error term, we specify the empirical model of the federal funds rate as:

$$r_t = \mu_t + \sigma_t v_t \,. \tag{13}$$

For all days of the maintenance period after the first, we model the conditional mean of r_t, $\mu_t = \mathrm{E}\left[r_t\right]$, as the sum of the previous day's rate r_{t-1} (which the martingale hypothesis suggests should be the only relevant variable known at time t-1) and assorted calendar effects (to account for failures of the martingale hypothesis). We control for level-shift effects of target rate changes on interest rate changes by including target rate changes as determinants of mean interest rates. Thus:

$$\mu_t = r_{t-1} + \delta_{s_t} + \kappa' k_t + \iota(r_t^* - r_{t-1}^*) \,, \quad t = 2,\ldots, T, \tag{14}$$

where $s_t \in \{2,\ldots,10\}$ is the day of the maintenance period associated with day t; δ_{s_t} is a constant specific to day s_t of the maintenance period; and k_t is a set of zero-one dummies for days before and after holidays and for end-of-quarter and end-of-year days, to control for window-dressing operations on reporting dates (see Allen and Saunders, 1992, for relevant evidence).

Given reserve-carryover limits, r_t need not follow a martingale across maintenance periods. Hence, we model the conditional mean on the first day of each period by an autoregressive model, which we estimated as a function of the changes in the federal funds rate between day 8 and day 9 and between day 9 and day 10 of the previous maintenance period:

$$\mu_t = r_{t-1} + \phi_1(r_{t-1} - r_{t-2}) + \phi_2(r_{t-2} - r_{t-3}) + \delta_1 + \kappa' k_t + \iota(r_t^* - r_{t-1}^*) \ , \quad t = 1 \ . \tag{15}$$

We model the variance of the federal funds rate, $\sigma_t^2 = \mathrm{E}\left[(r_t - \mu_t)^2\right]$, as a function of day-of-maintenance-period effects, ξ_{s_t}; calendar effects, h_t; the number of nontrading days between trading days t-1 and t, N_t; and the target rate as a proportion of the penalty rate, z_t. The vector h_t includes end-of-year and end-of-quarter dummies and two more dummies: a first dummy for the 1986-1987 period, during which the Fed did not implement a strict interest-targeting procedure and which may be associated with higher volatility; and a second dummy for the maintenance periods from 1/10/1991 to 2/6/1991, which immediately followed the early-1991 reform in reserve requirements and during which volatility was also extraordinarily high. Among the determinants of the rate's variance we also include a dummy valued at one on days when a target change was implemented and zero otherwise.

We also introduce "Exponential GARCH" effects (Nelson, 1991), and allow for asymmetric effects of lagged innovations ν_{t-1} on each day's variance. The EGARCH(1,1) model we estimate allows for persistent deviations of the (log of) the conditional variance from its unconditional expected value, $\xi_{s_t} + \omega' h_t + \zeta z_t + \log(1 + \gamma N_t)$. Standard ARCH tests did not reveal residual conditional heteroskedasticity, and coefficients associated with the second lag were insignificant. Following Nelson, the parameter γ measures the effect of previous nontrading days N_t on day t's variance. To test theoretical predictions on the effects of different target rates, the variable z_t, defined as one minus the ratio of target to penalty rates, is included among the determinants of the federal fund rate's variance.[5]

The resulting model for the variance of the federal funds rate is:

$$\log(\sigma_t^2) - \xi_{s_t} - \omega' h_t - \zeta z_t - \log(1+\gamma N_t) =$$
$$\lambda \left[\log(\sigma_{t-1}^2) - \xi_{s_{t-1}} - \omega' h_{t-1} - \zeta z_{t-1} - \log(1+\gamma N_{t-1}) \right] + \alpha \, |v_{t-1}| + \theta \, v_{t-1}, \quad t = 1,\dots T. \quad (16)$$

A main implication of our theoretical work is that the time profile of interest rate volatility should reflect the Fed's inclination to accommodate liquidity shocks. To test this hypothesis we split our data into three samples: a first ("pre-1994") sample including maintenance periods prior to February 1994 in which no FOMC meeting took place; a second ("post-1994") sample including post-February 1994 periods in which no FOMC meeting took place; and a third ("FOMC") sample including periods (pre- and post-February 1994) in which an FOMC meeting took place. This split is suggested by the Fed's operational changes in February 1994, whereby changes in target rates have been publicly announced and implemented mostly after FOMC meetings. Target rate changes in the post-1994 sample should be viewed as less likely than in the other two samples; also, the Fed is likely to have become less reluctant to undertake large operations, as these could not be perceived as signals of policy shifts. According to our model, this should imply a lower and flatter profile of interest rate volatilities as a function of the maintenance period. To test this hypothesis, we include in the model of the variance three sets (one for each sub-sample) of 10 day-of-maintenance-period dummies. (We also estimated a model splitting the FOMC sample into pre- and post-1994 samples. The split coefficients, however, were found to be insignificantly different from each other.)

Finally, we assume a t-distribution for the innovations v_t, and obtain maximum likelihood estimates of the parameters--including the degrees of freedom of the t-distribution--by numerical optimization. This specification allows us to match well both the fat tails and the concentration of small changes found in the empirical distribution of interest rates.[6] To circumvent convergence problems induced by the non-differentiability of the EGARCH variance at the origin, we followed Andersen and Lund (1997, p. 351) in setting $|v_t|=|v_t|$ for $|v_t|\geq\pi/2K$, and $|v_t|=(\pi/2-\cos(K\,v_t))/K$ for $|v_t|<\pi/2K$. Any large value of K yields a close and twice-differentiable approximation to $|v_t|$; we set K=20.

4.3. Results. Table 2 and Figure 7 summarize our results. First, consider estimates of calendar and EGARCH effects, introduced to clean the data of effects we do not model theoretically. The federal funds rate falls on the last working day of the year; its variance on that day, and the two days before and after it, is 17 times larger than on a typical day. The rate tends to rise considerably on the last business day of quarters 1, 2, and 3, and to fall the day after, with a variance 8 times larger than on a typical day. The rate tends to fall on days preceding holidays and to rise on the following days. Each nontrading day raises the variance of the first following trading day by about 67 percent. The variance is also marginally higher in the 1986-87 period, when the Fed did not follow a strict interest-targeting procedure, and significantly higher at the beginning of 1991, right after a reform in reserve requirements. The EGARCH parameters are strongly significant, suggesting persistence in the volatility of the underlying liquidity-shock process. The estimated degrees of freedom of the Student-t distribution, 2.94, are insignificantly different from 3 (the p-value is 0.747) and imply a very fat-tailed distribution of the errors. The significance of the day-of-period dummies k_t implies a rejection of the martingale hypothesis, supporting evidence uncovered by Hamilton (1996) and others, and explained by Hamilton as reflecting transaction costs, lines of credit, and other imperfections of the funds market.

Next, consider maintenance-period effects on interest rate volatility. Figure 7 plots the estimated profiles of the standard deviation of interest rates' daily changes. In all subsamples, the volatility reaches a minimum between the second and third day of the period. Higher volatility between the first and second day probably reflects carry-over effects: early in each period, banks must often unwind positions opened to satisfy requirements in the previous period.

Patterns of interest rate volatility are otherwise consistent with our model's predictions. The volatility of interest rate changes rises through the rest of the period. The estimated variance is extraordinarily high on the last day of the maintenance period (in the pre-1994 sample, it is 42 times larger than its low on day 3 and 7 times larger than its value on day 9). Most interestingly, the post-1994 volatility profile is closer than the other two volatility profiles to the profile one would expect with perfect Fed targeting. A Wald test of the 9 equality restrictions between same-day-of-maintenance-period pre-94 and post-94 coefficients yielded a χ^2 of 27.70 and a *p*-value of 0.001. In particular, coefficients of the post-1994 dummies tended to be significantly smaller than those of the pre-1994 and FOMC dummies towards the end of the maintenance period. A similar test accepted, instead, the equality between pre-94 and FOMC coefficients: the Wald test of the 9 relevant restrictions yielded a χ^2 of 8.37 and a *p*-value of 0.497. This evidence confirms our prediction that biweekly volatility patterns should be less pronounced when the public's confidence in the Fed's commitment to the current target is greater, i.e., in periods when intervention takes place in a deeper market, and in periods when targets are transparently announced and altered mainly on the occasion of FOMC meetings.

Finally, our estimates indicate that a higher target rate (with respect to the penalty rate) decreases the variance of the federal funds rate. This effect is strongly significant and robust across empirical specifications. According to our estimates, an increase in the target rate from ½ to ¾ the penalty rate would reduce the variance of the federal funds rate by almost 30 percent.

5. Concluding remarks

We study the interaction between the Fed's targeting activity and banks' reserve-demand behavior, in a model of the federal funds market which goes some way towards bridging the methodological gap between textbook monetary theory and the micro-analysis of money markets. The market's equilibrium, represented by a set of S-shaped relationships linking interest rates and bank reserves, features a realistic high-frequency heteroskedasticity of interest rates and links it to the style of the Fed's procedures. The model suggests that patterns of interest rate volatility should reflect the confidence with which market participants view the Fed's commitment to target interest rates. Analysis of U.S. data confirms that transparent targeting and the tendency to change targets only after FOMC meetings since 1994 have been associated with less pronounced biweekly patterns of interest rate volatilities, and with lower volatility on and immediately before settlement days than in the pre-reform period.

We view our analysis of the daily behavior of the funds market as a starting point to study more closely the micro-foundations of monetary policy and--conversely--to bring monetary considerations into the analysis of financial markets. Our stylized model, of course, could be expanded and improved. For instance, we focus on the positive aspects of Fed intervention, as we see it historically implemented. A normative analysis, building on our model to study the welfare implications of alternative policies, would be a logical next step of research.

Also, the model is focused on high-frequency interest rate patterns, which we analyze from a quite different perspective than traditional macro-models of monetary policy. Mechanical time aggregation of our high-frequency model need not automatically yield a model suitable for quarterly or annual frequencies. However, our model's emphasis on the role of imperfect Fed accommodation of liquidity shocks is in many ways similar to that of lower-frequency studies of Fed behavior, such as Bernanke and Mihov (1998) and Gali (1998).

Finally, we do not incorporate a number of market imperfections on which previous studies have relied to explain federal funds rates' departure from their benchmark martingale behavior. We also abstract from non-interbank channels banks may use to borrow and lend funds, and from non-pecuniary penalties banks face when incurring reserve deficiencies, such as more intense Fed scrutiny, rationing of future loans, and signals of the institution's financial weakness. Yet we find it interesting that no market imperfection needs to be invoked to explain the main high-frequency patterns in funds rates' volatility: these patterns emerge naturally from the interaction of banks' optimizing behavior and the Fed's intervention procedure, and offer useful information as to the latter's character on a day-to-day basis.

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2. In another interesting recent change, in October 1999 the FOMC authorized the Fed's Open Market Desk to accept a broader pool of collateral for its repo operations, including mortgage-backed securities issued by federal agencies. (Previously, only agencies' direct obligations were included.) This authorization was granted to limit the risk of liquidity shortages connected with Y2K, and was to expire in April 2000. However, the FOMC extended this authority through end-2000, pending its review of the Desk's ability to operate with a reduced supply of Treasury debt. Quantitatively, this innovation is unlikely to yield significant changes in patterns of interest rate volatility. (The change also took place outside our sample period.) But the concern that the Fed expressed with limits to its ability to intervene matches the motivation for much of our analysis, which suggests that, in theory, broadening collateral should reduce the funds' rate daily volatility.

3. To see this, note that $\mathrm{E}[\mathrm{Prob}(Y \le X) \mid X] = \mathrm{Prob}(Y \le X)$. Hence, if $X \sim N(\mu, \tau^2)$ and $Y \sim N(0,1)$, then $\mathrm{E}[\Phi(X)] = P\left((Y - X + \mu)/\sqrt{1+\tau^2} \le \mu/\sqrt{1+\tau^2}\right) = \Phi\left(\mu/\sqrt{1+\tau^2}\right)$, since sums of normal random variables are normally distributed. The assertion in the text follows from setting $\mu = -t\tilde{a}_t/\sigma_\epsilon$ and $\tau^2 = (T-t)(\sigma_\epsilon^2 + \sigma_v^2)/\sigma_\epsilon^2$. We thank Søren Johansen for suggesting this argument.

4. Stigum (1990) quotes a Federal Reserve official as follows: *"The market is often incapable of handling a large amount--either because on the repo side they lack collateral or because on the reverse side we have exhausted the supply of banks that want to do reverses. «Banks who do*

reverses with us are not as welcome at the discount window as they would be if they did not. So banks are reluctant to do reverses because they fear the money market might tighten and they might have to come into the discount window. The rationale for this policy is that a bank should not borrow from us money that they have in fact lent us.»"

5. Recently, required reserves have declined sharply as banks have begun to "sweep" balances overnight into non-reservable liabilities such as savings accounts, a practice viewed as potentially leading to greater *intraday* interest rate volatility (Bennett and Hilton, 1997). Our theoretical model focuses on *overnight* developments, and is not designed to deliver predictions on the behavior of intraday interest rates. Yet, in our empirical work we explored whether we could identify effects from falling required reserves to the daily volatility of federal funds rates. We did so by including required reserves as a regressor in (16). The resulting coefficient had the expected negative sign, but was statistically insignificant; other coefficients were essentially unchanged.

6. Confirming this property, a quantile-quantile plot of the distribution of estimates of v_t against a randomly generated t-distribution (with the estimated degrees of freedom) was very close to a straight line. To verify the robustness of our results to the assumed distribution of the errors v_t, we re-estimated the model using a Generalized Error Distribution (GED), obtaining very similar results. Hamilton (1996, 1997) captures the same features by a mixture of normal distributions for the innovations.

Table 1. Timing of the Model in Day t

- The Fed injects or withdraws m_t to target r^*
- A first liquidity shock ν_t is realized
- Given mid-day average reserve balances $\tilde{a}_{it}$, banks borrow b_{it} overnight at the rate r_t
- A second liquidity shock ϵ_t is realized
- End-of-day average reserve balances a_{it} are computed
- If $t = T$, penalties on reserve deficiencies are imposed at the rate $\bar{r}$

Table 2. The empirical model of the federal funds rate

(standard errors in parenthesis)

	mean parameters		variance parameters (days 2-10 as deviations from day 1)					
	full sample		pre-1994 (no FOMC)		post-1994 (no FOMC)		FOMC	
Day-of-the-Maintenance-Period Effects	δ_s		ξ_s		ξ_s		ξ_s	
Day 1	0.022	(0.006)	-3.720	(0.293)	-3.756	(0.336)	-3.545	(0.323)
Day 2	-0.064	(0.005)	-0.293	(0.224)	-0.644	(0.288)	-0.372	(0.282)
Day 3	0.061	(0.005)	-1.386	(0.296)	-1.471	(0.347)	-1.394	(0.318)
Day 4	-0.052	(0.004)	-1.169	(0.244)	-0.724	(0.307)	-1.143	(0.287)
Day 5	-0.031	(0.004)	-1.222	(0.234)	-0.459	(0.320)	-0.781	(0.285)
Day 6	0.015	(0.004)	-0.636	(0.245)	-1.016	(0.325)	-0.754	(0.294)
Day 7	-0.041	(0.004)	-0.765	(0.245)	-1.080	(0.340)	-0.651	(0.305)
Day 8	0.087	(0.006)	-0.576	(0.308)	-1.336	(0.362)	-0.951	(0.327)
Day 9	-0.061	(0.006)	0.348	(0.239)	-0.013	(0.309)	-0.027	(0.284)
Day 10	0.137	(0.016)	2.344	(0.200)	1.705	(0.262)	2.192	(0.223)
Calendar Effects	κ				ω			
t is the end-of-year	-0.185	(0.078)						
t is the end-of-year, or one of the previous or following two days					2.913	(0.331)		
t is the end-of-quarter	0.206	(0.034)						
t is one day after the end of the quarter	-0.190	(0.039)						
t is the end-of-quarter, or the previous or following day					2.081	(0.181)		
t precedes a 1-day holiday	-0.026	(0.017)						
t precedes a 3-day holiday	-0.018	(0.008)						
t follows a 1-day holiday	0.062	(0.018)						
t follows a 3-day holiday	0.209	(0.013)						
t is the day target changes					0.783	(0.262)		
t is before 1/1/1988					0.254	(0.154)		
t is between 1/10/1991 and 2/6/1991					3.243	(0.594)		
Other Effects								
fraction of day 10 change reversed on day 1 of the following period: ϕ_1	-0.824	(0.021)						
fraction of day 9 change reversed on day 1 of the following period: ϕ_2	-0.502	(0.027)						
day t change when the target rate is changed by 1 on the same day: ι	0.431	(0.050)						
fraction by which each previous non-trading day raises the variance of day t: γ					0.668	(0.195)		
effect of (Penalty-Target)/Penalty: ζ					1.240	(0.465)		
Exponential GARCH Effects								
effect of t-1 log variance on today's log variance: λ					0.600	(0.038)		
effect of *absolute* value of t-1 innovation on today's log variance: α					0.718	(0.069)		
effect of *positive* t-1 innovation on today's log variance: θ					0.276	(0.042)		

Figure 1
No Fed intervention

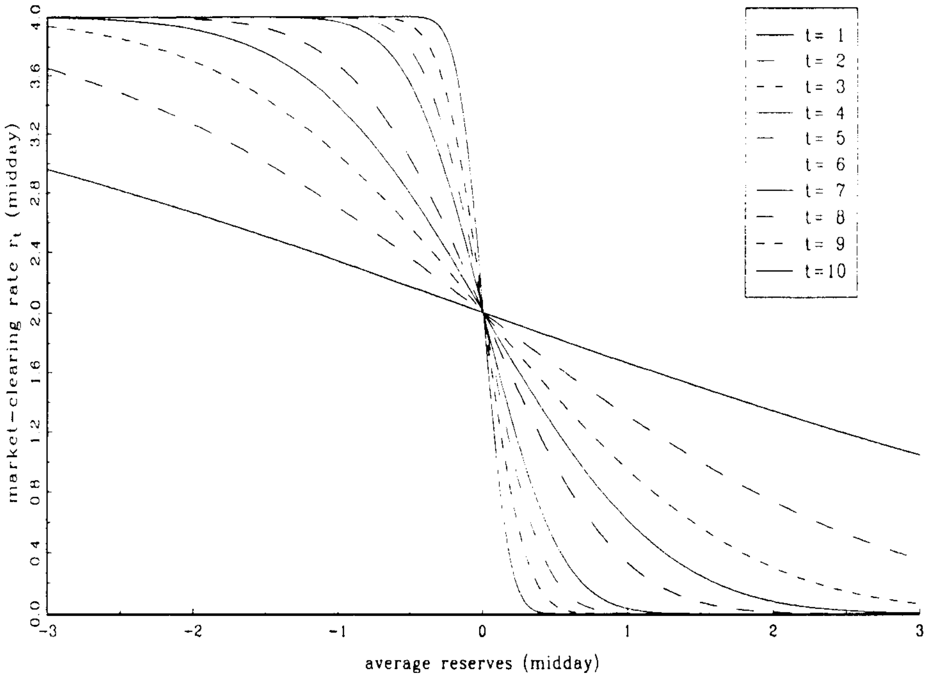


Figure 2
Fed intervention to enforce target

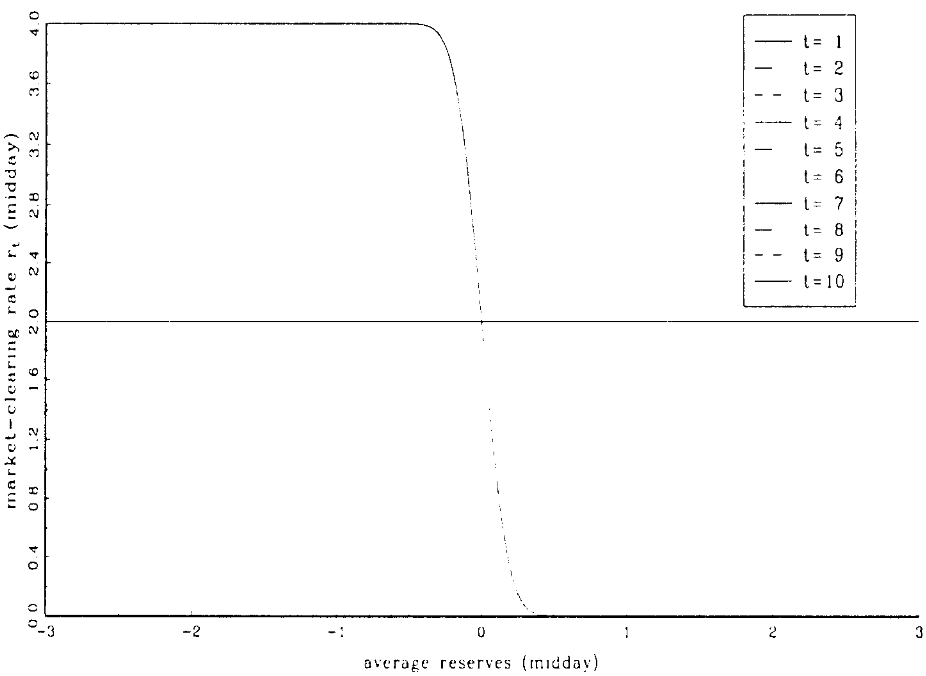


Figure 3
Daily volatility of federal funds rates' changes

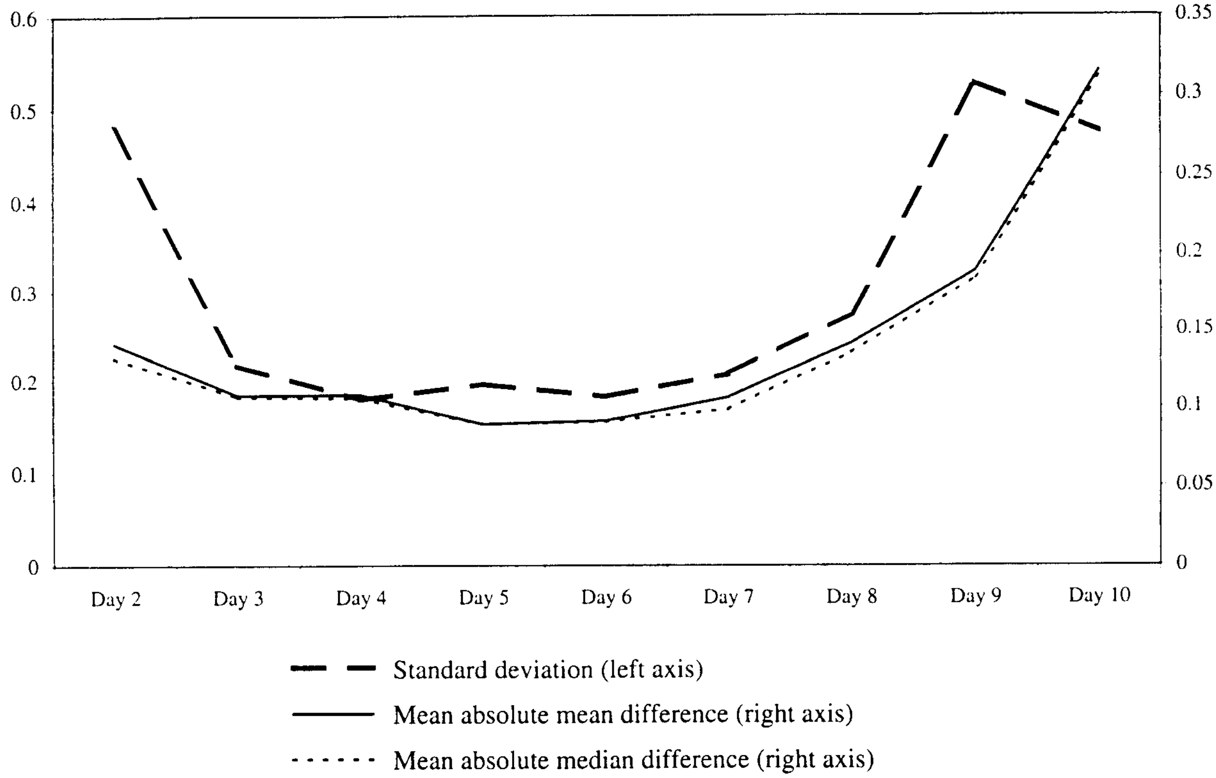
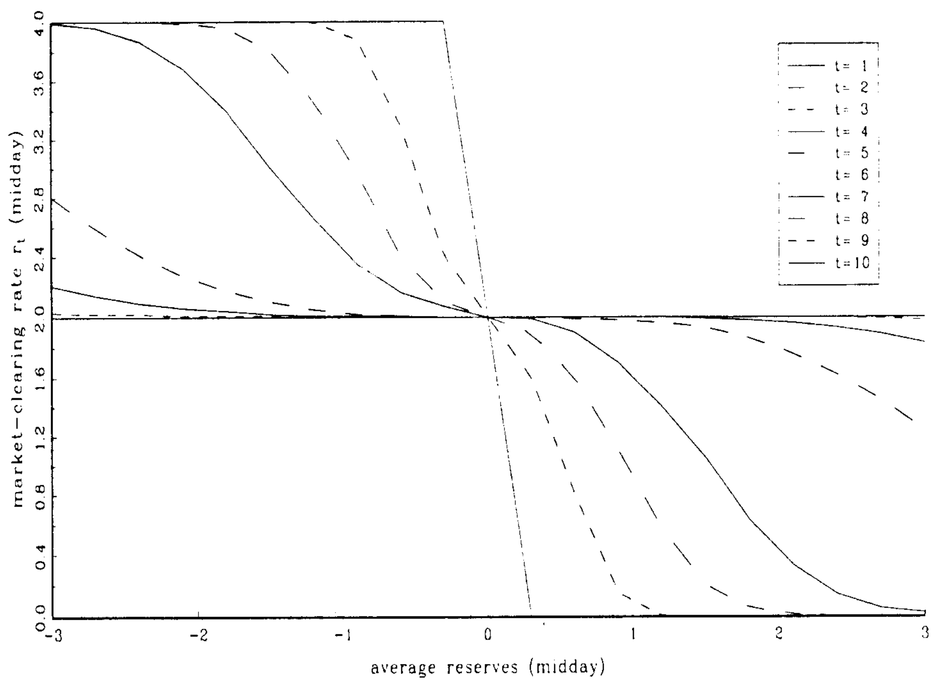


Figure 4
Fed intervention with RP limits



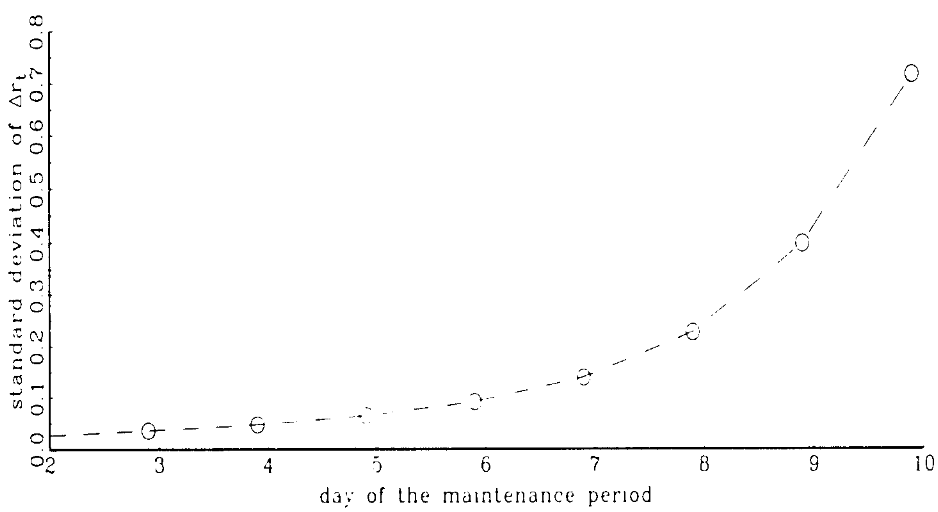


Figure 5
Effect of different RP limits on Fed intervention

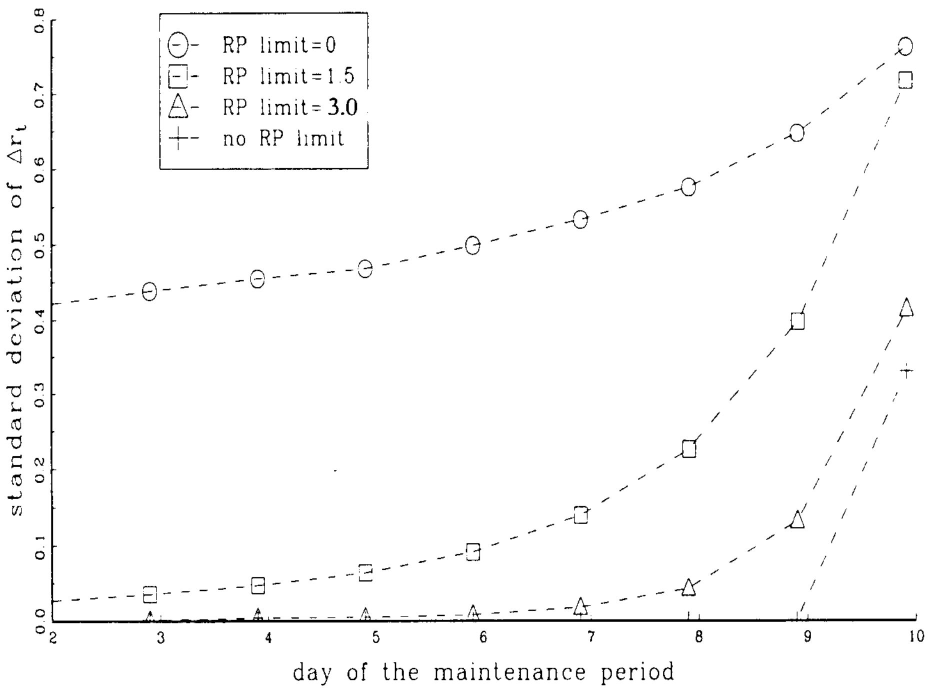


Figure 6
Effect of higher target rate

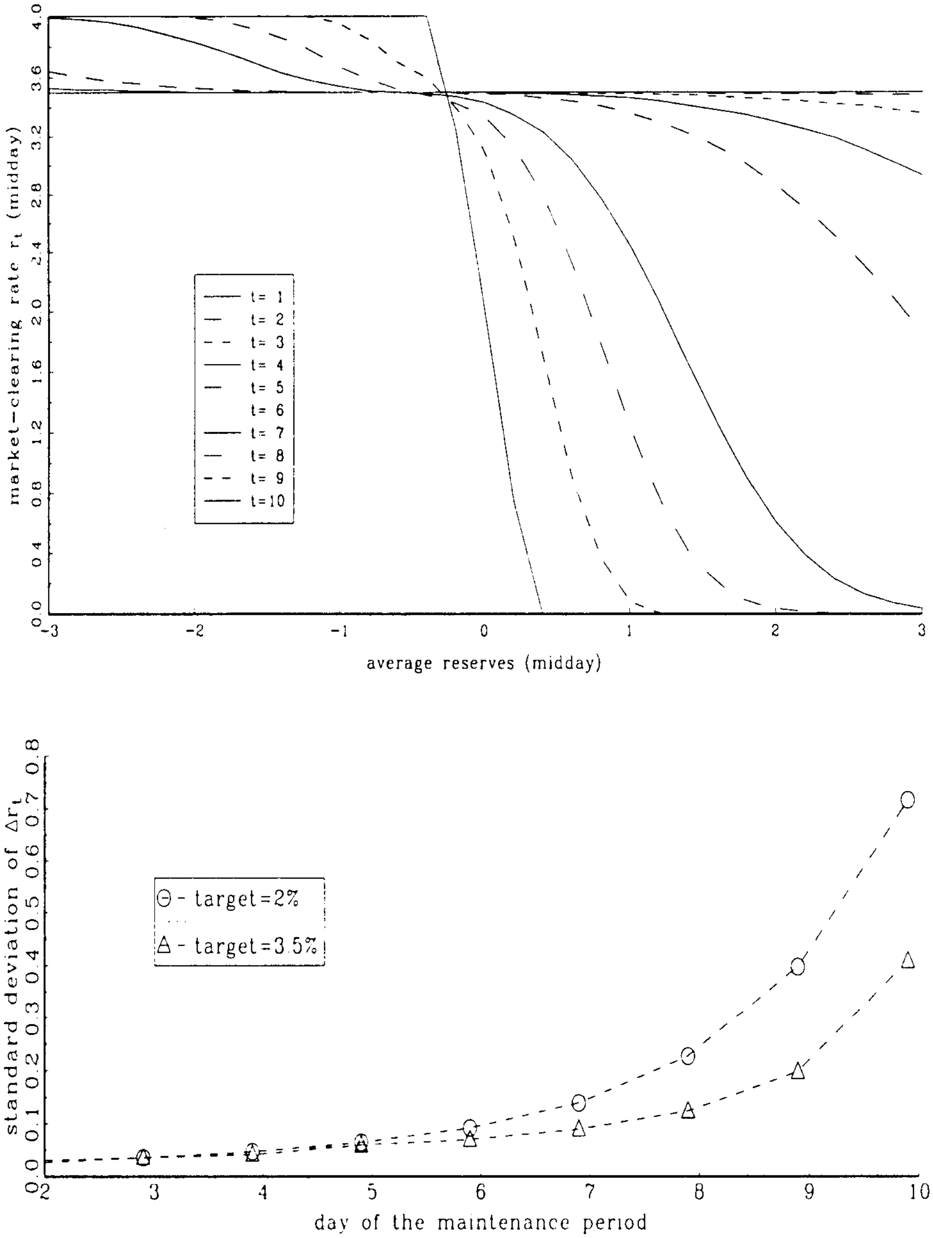
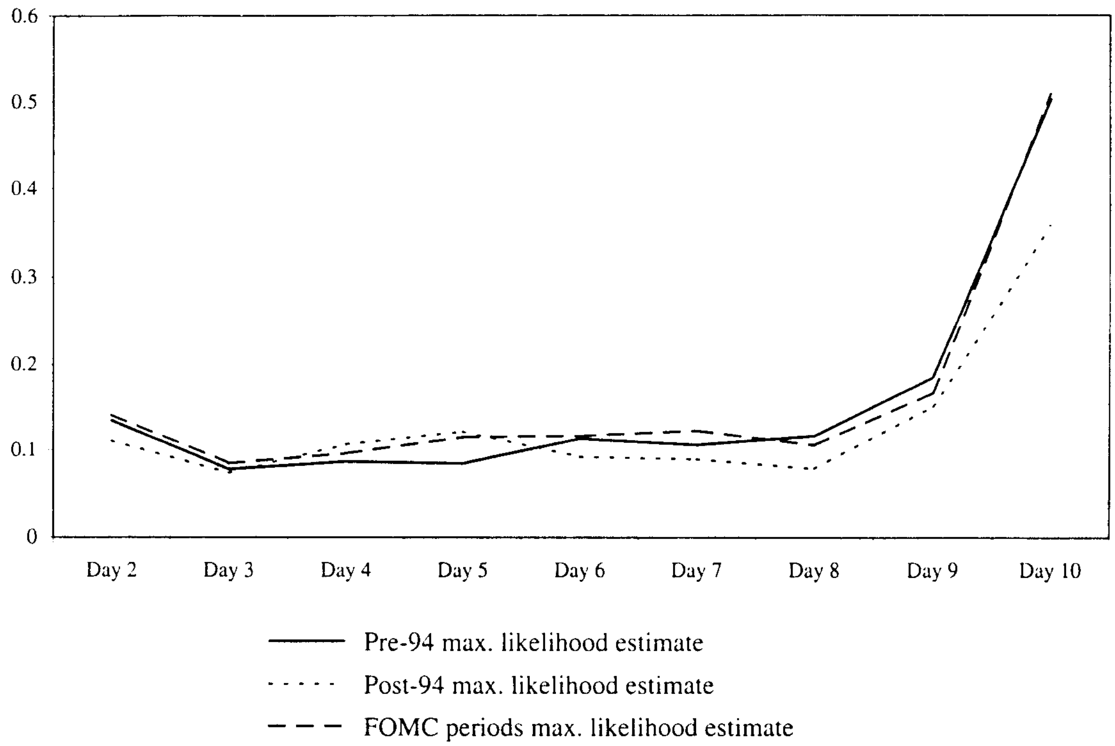


Figure 7

Estimated daily standard deviation of federal funds rates' changes



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