Declining Required Reserves and the Volatility of the Federal Funds Rate

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Abstract

Low required reserve balances in 1991 led to a sharp increase in the volatility of the federal funds rate, but similarly low balances in 1996 did not. This paper develops and simulates a microeconomic model of the funds market that explains these facts. We show that reductions in reserve balances increase the volatility of the federal funds rate, but that this relationship changes over time in response to observable changes in bank behavior. The model predicts that a continued decline in required reserves could increase funds-rate volatility significantly.

1. Introduction

In late 1990, the Federal Reserve reduced reserve requirements on nonpersonal time deposits and Eurocurrency liabilities from three percent to zero. Banks can satisfy reserve requirements by holding vault cash and balances at the Federal Reserve. Because the cut in requirements had little effect on banks' desired vault cash, it had a large effect on required reserve balances, as seen in Figure 1.[1] Accompanying this decline in reserve balances was a dramatic increase in the volatility of the interest rate that banks pay each other to borrow reserve balances, namely the federal funds rate. Figure 2 shows that the standard deviation of the daily difference between the actual funds rate and the Federal Open Market Committee's intended rate surged to about 80 basis points in early 1991, or nearly four times the level that prevailed prior to the cut in reserve requirements. Later that year, required reserve balances were boosted by rapid growth of transactions deposits and other factors, and funds-rate volatility subsided. Since early 1994, however, required reserve balances have fallen significantly, reaching their 1991 trough in early 1996. This decline can be attributed primarily to the emergence of so-called "retail sweep programs," in which banks shift deposits from reservable accounts (like NOW accounts) to non-reservable ones (like money market deposit accounts) without impairing depositors' access to the funds.[2] Yet, despite the large drop in required balances, Figure 2 shows that funds-rate volatility increased only slightly, and remained well below its level of early 1991.

Why was the low level of required reserve balances in 1991 accompanied by a sharp

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[1] We discuss the "required clearing balances" also shown in Figure 1 later in the paper.

[2] See Federal Reserve Board (1996b) for further discussion of sweep accounts. Required reserve balances have also declined because of an increase in banks' desired vault cash.

increase in the volatility of the federal funds rate, while the recent low levels of required balances have not been? Would further declines in required reserve balances eventually lead to much greater funds-rate volatility? In this paper, we develop and simulate a model of the funds market that addresses these questions. We estimate individual banks' demands for reserve balances and sum these demands across a large number of banks to arrive at an aggregate demand curve. We use this specification of demand to simulate the behavior of the federal funds rate in response to declining required reserves.

Our analysis shows that reductions in required reserve balances do increase the volatility of the federal funds rate, but that this relationship is quite nonlinear and changes over time in response to observable changes in bank behavior. Based on our parameter estimates, the simulated model can explain both the very high volatility of early 1991 and the more normal volatility of 1996. The model also predicts that continued declines in required reserves could increase funds-rate volatility significantly.

This result naturally raises another question, which is how the volatility of the federal funds rate matters. Would an increase in funds-rate volatility be only a technical reserve management concern for the Federal Reserve, or would it have broader financial market or macroeconomic implications? A complete answer to this question is beyond the scope of the present paper. We suspect that increased funds-rate volatility would have fairly small effects beyond the reserves market itself, but this outcome is by no means certain.[3] Deviations of the

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[3] See Sellon and Weiner (1996) for discussion of recent declines in required reserves in a number of countries, and some implications for monetary policy. Some financial-market participants in the United States do appear to be concerned about a possible rise in funds-rate volatility. For example, see the discussions of low reserve balances and funds-rate volatility in Wrightson Associates (1996a, 1996b, 1997).

funds rate from the intended rate would be larger, but the deviations should show little, if any, serial correlation across days. As a result, volatility of the maintenance-period average federal funds rate should rise a little but remain fairly low, and the volatility of longer-term rates should be even less affected. Nevertheless, an increase even in daily volatility would complicate banks' attempts to manage their reserve balances. It is also possible that greater volatility of the funds rate might have other adverse effects on financial markets. If this situation arose, the Federal Reserve might need to consider alternative procedures for implementing policy that would limit funds-rate volatility.

The remainder of this paper is organized as follows. The second section presents a simple model of bank demand for reserve balances, and shows why the level of required balances affects the volatility of the funds rate. The third section describes our procedure for estimating and simulating the model. The fourth section presents the simulation results, and the fifth section concludes.

2. The Demand for Reserve Balances

Our model views the federal funds rate as determined by the market for account balances at the Federal Reserve. The Fed controls the funds rate by predicting banks' demand for these balances and varying the supply accordingly. But there is unpredictable variation in demand as well as shocks to supply, so the Fed's control is imperfect.[4] As a result, the actual federal funds

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[4] See Meulendyke (1989) and Feinman (1993) for detailed accounts of the Fed's daily operating procedures.

rate does not precisely equal the Fed's target rate on most days. Moreover, there can be substantial variation in the funds rate over the course of a day, and this intraday volatility jumped dramatically in early 1991 when interday volatility increased. Analyzing intraday volatility is beyond the scope of this paper, however, and we assume throughout that there is a single daily market for reserve balances.[5] The corresponding federal funds rate is the "effective" rate, which is the volume-weighted mean of all trades reported by brokers to the Federal Reserve Bank of New York. The purpose of this paper is to examine the connection between the level of required reserves and the interday volatility of the effective federal funds rate. We begin in this section by examining and modelling banks' demands for reserve balances.

Why Do Banks Hold Reserve Balances?

One reason that banks hold account balances at the Federal Reserve is to meet reserve requirements. Required reserve balances are simply the portion of required reserves not met with vault cash.[6] These requirements are specified in terms of an *average* level of maintained balances over a two-week maintenance period, allowing banks considerable flexibility in managing their *daily* reserve position[7]. For example, if a bank's Fed account balance dips unexpectedly on a particular day, it can simply hold somewhat higher balances over the

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[5] For analysis of intraday volatility, see VanHoose (1991) and Lasser (1992). Because funds-market trading is typically not collateralized, the funds rate can also differ across borrowers according to their perceived riskiness. We abstract from this issue as well.

[6] Vault cash available to satisfy reserve requirements in the current maintenance period is based on vault cash held during the previous maintenance period.

[7] The two-week average structure for reserve requirements applies to banks with more than $4.3 million in reservable deposits and at least $57 million in total deposits. A separate structure applies to other banks with positive reserve requirements.

remainder of the maintenance period. Conversely, if a bank's Fed account balance climbs higher than expected, it can hold lower balances on following days. Of course, such flexibility is more limited on the last day of a maintenance period--termed the "settlement day"--and our empirical work models settlement days separately from other days.

This ability to substitute balances from one day to the next within a maintenance period helps to stabilize the federal funds rate. For example, if the federal funds rate on a particular day moves above the level expected to prevail over the remainder of the period, a bank can sell additional funds in the market (running down its reserve balances), thereby relieving some of the upward pressure on the funds rate. It is not necessary for this argument that reserve balances on different days of a maintenance period be *perfect* substitutes, but simply that there be some substitutability. Of course, our empirical results depend on the degree of substitutability that we estimate.

A second reason that banks hold reserve balances is to meet clearing balance requirements. Unlike other reserve balances, balances held to meet clearing balance requirements earn implicit interest in the form of earnings credits against charges for Federal Reserve priced services, such as check processing and cash shipments. As a result, banks voluntarily commit to hold such balances, and the label "required" may seem a misnomer. Yet, the commitment must be made in advance, and a bank that does not meet the commitment (less some small carryover provisions) is penalized.[8] Like required reserve balances, required clearing balances are specified in terms of an average level of balances over the two-week maintenance period.

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[8] The penalty equals two percent of deficiencies up to twenty percent of an institution's clearing balance requirement, and four percent of any portion of a deficiency exceeding twenty percent of the requirement.

Thus, for the purpose of this paper, the two types of required balances are essentially equivalent, and we will refer to them together as "required operating balances."

Figure 1 shows that the volume of required clearing balances has increased substantially over the past several years. Many banks that have experienced declining required reserve balances have instituted required clearing balances, presumably because it simplifies the management of their account with the Fed, as will become clear later in this section. In any event, required operating balances have fallen by less during this period than required reserve balances, although still by a substantial amount. Early in 1997, required operating balances fell below their level in early 1991.

Apart from reserve and clearing balance requirements, another important factor underlying the demand for account balances at the Federal Reserve is the desire to avoid account overdrafts. Banks process a huge volume of payments over Fedwire each day, but must end the day with a positive position in their Fed accounts. The Fed charges a substantial penalty for overnight overdrafts, and frequent overdrafts can result in the imposition of administrative controls.[9] As a result, banks are quite determined to achieve non-negative balances in their accounts at the end of the day, and generally try to maintain some positive level of balances late in the day as insurance against unexpected transactions that might result in an overdraft. For example, banks responding to the Fed's Senior Financial Officer Survey in May 1996 (Federal Reserve Board, 1996a) reported a median desired minimum balance in their Fed account of $18 million at the

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[9] Overnight overdrafts are charged a penalty rate of four percentage points over the effective federal funds rate on the day of the overdraft, with a minimum charge of $100. Higher overdraft charges are applied if an institution exceeds three overdrafts in a moving twelve-month period. Chronic overdraft problems may also result in other account controls or a mandated clearing balance requirement.

close of Fedwire, with some banks reporting desired minimum balances as high as $100 million.

This clearing, or precautionary, demand for reserve balances is a *daily* demand, so it can constrain banks' ability to substitute balances across days of a maintenance period. This constraint is unlikely to be binding when required operating balances are high, because the level of balances that banks hold each day in order to meet requirements is more than sufficient to guard against overdrafts. When required operating balances are low, however, they may be close to or below the level of balances that banks want to hold to avoid overdrafts. A bank may try to stay out of this situation by increasing its clearing balance requirement when its required reserve balance declines, but this strategy is limited by the amount of priced services that the bank uses.

Clearing demands are likely to be quite unresponsive to interest rates, as many banks are willing to pay very high rates of interest on funds in the market to avoid overdraft penalties and administrative controls. Banks have the option of borrowing reserves from the Fed's discount window, and the *explicit* cost of such borrowing is below the federal funds rate. Yet, banks apparently believe that the *implicit* cost of discount borrowing is high, as the amount of borrowing has fallen to very low levels in recent years.[10] Our numerical estimates of the elasticities of clearing and requirement-related demand (which are described in the Appendix) implicitly incorporate the elasticity of discount-window borrowing. In any event, as required operating balances decline and banks' underlying clearing demands become more evident, the aggregate reserve demand curve tends to steepen. This produces larger changes in the federal

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[10] See Meulendyke (1992), Clouse (1994), and Peristiani (1994) for empirical analyses of discount window borrowing.

funds rate in response to given shocks to the demand and supply of reserve balances. In the rest of this section we model the demand for balances in a way that makes this story more precise.

A Switching Model of Bank Behavior

A simple way of capturing the intuition in the previous section is to specify the demand for reserve balances by an individual bank as the *maximum* of two distinct demand schedules: a "requirement-related" demand and a "clearing" demand. An alternative approach would be to use an explicit maximizing model of bank behavior in the reserve market.[11] However, such models generally yield rather complex expressions for individual bank's reserve demands, which would be computationally burdensome in a simulation exercise involving heterogeneous banks. The requirement-related reserve demand schedule describes the balance that an individual bank desires to hold each day to meet reserve and clearing balance requirements. Note that this balance includes not just the required amounts, but also the average amount of excess reserves that a bank would hold to ensure--in the face of various shocks--that it actually met the requirements. We describe the requirement-related demand of bank j on day t by:

$$R_{jt} = L_j e^{(-\alpha i_t + u_{jt})} ,$$

where i_t is the difference between the actual and intended federal funds rate, α is the interest semi-elasticity of requirement-related demand, u_{jt} is a random shock to requirement-related demand, and L_j is the desired requirement-related balance when the actual funds rate equals its

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[11] See, for example, Ho and Saunders (1985) and Spindt and Hoffmeister (1988).

intended value and there are no shocks.[12]

The clearing reserve demand schedule describes the balance a bank desires to hold each day to avoid overnight overdrafts. We model the clearing demand of bank j on day t by:

$$C_{jt} = K_j e^{(-\beta i_t + v_{jt})} ,$$

where β is the interest semi-elasticity of clearing demand, v_{jt} is a random shock to clearing demand, and K_j is the desired clearing balance when the actual funds rate equals its intended value and there are no shocks.

The expressions for R_{jt} and C_{jt} include shocks that are specific to each bank. We can envision each shock as consisting of two parts: one part is an aggregate shock that is common to all banks, and one part is an idiosyncratic shock that is uncorrelated across banks. We discovered that the idiosyncratic part of these shocks had very little effect on the simulated level of funds-rate volatility. In the interest of simplicity, therefore, the shocks used in this paper are aggregate shocks and hence perfectly correlated across banks.

Putting these pieces together, the "effective" demand for reserve balances by bank j on day t can be described by:

$$D_{jt} = \max\left(R_{jt}, C_{jt}\right) = \max\left(L_j e^{(-\alpha i_t + u_t)}, K_j e^{(-\beta i_t + v_t)}\right) . \qquad (1)$$

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[12] This specification assumes that in the absence of random shocks or funds-rate variation, banks would choose to hold the same amount of reserve balances on each day of a maintenance period. Griffiths and Winters (1995) explain why banks may deliberately run short on reserves early in a period to avoid accumulating more excess reserves than can be offset later. Yet, a number of large institutions responding to the Fed's Senior Financial Officer Survey (Federal Reserve Board, 1996a) claim to follow a constant balance strategy like that assumed here.

Following the discussion above, the clearing demand for reserves is assumed to be steeper than the requirement-related demand for reserves ($\beta < \alpha$). The upper panel of Figure 3 depicts a possible set of demand schedules for bank j. When the federal funds rate is close to its target value, this bank finds that its requirement-related reserve demand schedule is binding. When the funds-rate deviation exceeds the critical value i_j^*, however, the steeper clearing demand becomes binding. The critical value i_j^* is the value of the funds-rate deviation at which the requirement-related and clearing demands are equal:

$$i_{jt}^* = (\alpha - \beta)^{-1} (l_{jt} - k_{jt} + u_t - v_t) \quad ,$$

where l_{jt} equals $\log(L_{jt})$ and k_{jt} equals $\log(K_{jt})$. Thus, if required operating balances fall (l_{jt} declines) or the clearing demand for reserves is unusually high (v_t is large), the critical value i_{jt}^* falls and the bank's clearing demand schedule becomes binding over a wider range. Different banks will face different i_{jt}^*'s, of course, with negative values applying to banks with very low requirement-related demand.

One limitation in our modelling approach is the constant semi-elasticity of demand, which implies that banks are willing to hold very large quantities of reserve balances as the funds rate falls. For example, if $\alpha = 1$ and the funds rate falls two percentage points below its intended value, our specification implies that banks would hold more than seven times their normal balances. In the real world, however, banks are unwilling to hold more balances on a given day than they expect to be able to "run off" later in the maintenance period. Thus, at some level of reserve balances, a bank's requirement-related demand curve should fall sharply toward the horizontal axis in Figure 3.[13] By ignoring this constraint, our model requires exceptionally large demand or supply shocks to produce very low values of the funds rate, so our simulations produce fewer low values than we observe in the data. Yet, incorporating the constraint would involve a much more complicated daily demand schedule, and would force us to model the explicit linkages among the days of a maintenance period. Because most funds-rate volatility arises from higher-than-intended values anyway (since the actual funds rate never falls below zero), this great simplification in our model comes at fairly low cost.

Aggregation

Aggregate effective demand for reserve balances is the sum of the individual banks' effective demands:

$$\boldsymbol{D}_t = \sum_j \boldsymbol{D}_{jt} = \sum_j \max\left(\boldsymbol{R}_{jt}\,,\, \boldsymbol{C}_{jt}\right) \quad . \tag{2}$$

As the funds rate deviation i_t increases, it exceeds the critical values i_{jt}^* for a larger number of banks, which makes their clearing demands binding ($C_{jt} > R_{jt}$). Thus, as i_t increases to very high levels, aggregate demand converges to the sum of the individual banks' clearing demands. Similarly, as i_t declines to very low levels, more of the individual banks' requirement-related demands become binding ($C_{jt} < R_{jt}$), and the aggregate demand curve converges to the sum of

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[13] For example, on the last day of a maintenance period, a bank would not want to hold more excess reserves than it can "carry over" into the next period. Under current rules, a bank can carryover excess reserves up to four percent of its required reserves into the next maintenance period.

the individual banks' requirement-related reserve demands. For intermediate values of i_t, aggregate demand is greater than either the sum of banks' clearing demands or the sum of banks' requirement-related demands, as shown in the bottom panel of Figure 3. To see why, consider an increase in i_t from a very low level at which all firms are on their requirement-related demand schedules. All banks' requirement-related demands will fall (because of the interest elasticity of those demands), and for some banks they will fall below clearing demand, which will make the (greater) clearing demand binding. Thus, the aggregate demand for reserve balances falls by less than the requirement-related demand. In mathematical terms, aggregate demand is the sum of maximums for each bank, which must exceed the maximum of simple sums across banks.

Note that aggregate effective demand is curved, in contrast to the kinked effective demand of an individual bank. This difference arises because banks have different clearing needs relative to requirement-related balances, and at a given federal funds rate, some banks will tend to be constrained by clearing demand, while others will tend to be constrained by requirement-related demand.[14] One difference between our switching model and an optimizing model of bank behavior is that an optimizing model would predict a smooth demand curve for balances even at the level of an individual bank, because the bank would shift its attention between its two underlying demands gradually rather than abruptly. But because aggregation essentially smooths out our bank-specific kinks anyway, we do not believe that the kinks are affecting our results.

Some Observations Concerning the Demand for Reserve Balances and Funds-Rate Volatility

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[14] Strictly speaking, aggregate effective demand has thousands of small kinks, corresponding to the number of banks that participate in the funds market.

Many of the results from the simulation exercises below are straightforward implications of the nature of the aggregate demand for reserves. Here we discuss the effect of declining required reserves, of demand shocks, and of the distribution of required operating balances.

Declining Required Reserves. In principle, a decline in required reserves might have no effect on required operating balances, if it were accompanied by a sufficiently large decline in desired vault cash or a sufficiently large increase in required clearing balances. In practice, however, recent declines in required reserves have significantly reduced required operating balances, as shown in Figure 1. This change moves requirement-related demand to the left and makes clearing demand a more important component of effective demand. As a result, funds-rate volatility increases in two ways. First, as shown in the top panel of Figure 4, such a shift causes a steepening of the effective demand curve, which means that the funds rate would change by more for a given shock to reserve demand or supply. Second, the estimates we describe below imply that clearing demand fluctuates more on a day-to-day basis than does requirement-related demand, which also makes the funds rate more volatile.

Demand Shocks. Demand shocks in our model refer to any change in requirement-related demand or clearing demand that the Federal Reserve cannot foresee. Some of these shocks may be known in advance by bank reserve managers, and some will be surprises to them as well. An example in the former category would be a jump in the planned end-of-day balance in response to greater interbank transactions and the accompanying increase in the reserve manager's uncertainty. An example in the latter category would be the realization late in a maintenance period that a bank had more transactions deposits than anticipated and thus had a higher level of required reserves.[15]

The bottom panel of Figure 4 displays the impact of a positive shock to requirement-related demand, which shifts both aggregate requirement-related demand and aggregate effective demand to the right. Similarly, a common shock to bank's clearing demands--for example, the settlement of a Treasury auction that significantly increases the volume of interbank transactions and thus raises banks' uncertainty about their end-of-day balances--would shift aggregate clearing demand and aggregate effective demand to the right.

The Distribution of Required Operating Balances. Another notable feature of the aggregate effective demand curve is that its position depends on the joint distribution of required operating balances and clearing demands across banks. That is, aggregate demand is determined not only by the total amount of required operating balances, but also by the relationship between these balances and clearing demands at each individual bank. In principle, therefore, the volatility of the funds rate depends not only on the total amount of required reserves, but on which banks are facing these requirements. The effective demand for reserve balances could vary from maintenance period to maintenance period in response to changes in the distribution of reserve requirements across the banking system even though aggregate reserve requirements

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[15] Most banks operate under contemporaneous reserve requirements (CRR), in which the average quantity of reservable deposits at a bank during a two-week period ending on a Monday determines required reserves for the two-week maintenance period ending two days later. Prior to 1984, the Fed followed a system of lagged reserve requirements (LRR) in which the need for required reserves was known before the relevant maintenance period began. As explained by Lasser (1992), the switch from LRR to CRR increased banks' uncertainty, and thus should have raised funds-rate volatility (as demand shocks do in our model). At the same time, however, the maintenance period was lengthened from one week to two weeks, which our model predicts would have increased the elasticity of requirement-related demand and thus reduced funds-rate volatility. Lasser's empirical work suggests that volatility did increase immediately after the switch but subsided quickly.

remained constant.

3. Simulation Framework

In the previous section, we developed a microeconomic model of the demand for reserve balances and discussed some of its qualitative implications. In this section, we specify the aggregate supply of reserve balances and derive the associated expression for the equilibrium federal funds rate. We then describe our procedures for estimating the parameters of the model and conducting the simulations.

The Federal Reserve can change the quantity of reserve balances through open market operations, but the quantity outstanding on a given day is also affected by unpredictable events, which we discuss in more detail below. Thus, the supply of balances on day *t* equals:

$$S_t = A + w_t \quad ,$$

where A is the Fed's intended supply, and w_t is a random shock on that day. Equilibrium in the funds market on day *t* requires:

$$D_t = S_t \quad ,$$

which, combined with equations (1) and (2) above, yields:

$$\sum_j \max\left(L_j \, e^{(-\alpha i_t + u_{jt})} , K_j \, e^{(-\beta i_t + v_{jt})} \right) = A + w_t \quad . \tag{3}$$

Equation (3) summarizes our model of the reserves market. A significant hurdle in implementing this model empirically is the large number of parameters that it involves. Table 1 summarizes the parameter values that we use and our methods for estimating them. The Appendix describes those methods in detail, and we summarize them briefly here.

The model incorporates the behavior of 6000 banks that held 97 percent of total required operating balances in late 1995. We estimate the parameters using a combination of cross-section data on these banks and aggregate time series data on the reserves market. The average levels of requirement-related demand and clearing demand (the L_j's and K_j's) are based on actual reserve balances. The interest elasticity of requirement-related demand (α) is estimated following a procedure developed by Hamilton (1997). We are unable to estimate the interest elasticity of clearing demand (β), so we choose a value as described in the Appendix. The size of shocks to requirement-related demand (σ_u) is chosen to match the observed volatility of the funds rate in recent years *given* the other parameters in the model. The size of shocks to clearing demand (σ_v) is based on the volatility of reserve balances at banks that have no requirement-related demand. We describe our procedure for setting the intended supply of reserves (A) shortly. Finally, we estimate the size of supply shocks (σ_w) using time series data on the quantity of reserves and the Fed staff's estimates of factors affecting reserves supply.

Our simulation procedure is straightforward. We examine the behavior of the federal funds rate over 100 simulated settlement days and 100 simulated non-settlement days. Each day brings the same intended supply of reserves but a new set of shocks to requirement-related demand, clearing demand, and supply. After drawing 200 sets of shocks, we choose an initial value of intended supply A_o. Then we do a simple numerical search to find the deviation of the funds rate from its intended value that satisfies equation (3) on each day. Because we assume that the Federal Reserve can achieve its funds rate target on average, we adjust the intended supply A until the mean funds-rate deviation across simulated days is less than half a basis point in absolute value.

4. Results

The model developed in the previous sections can now be used to study the effect of low required operating balances on the volatility of the federal funds rate. We examine the likely impact of future declines in required reserves, and also explain why the funds rate was so volatile in early 1991.

The Effect of Declining Required Reserves

Required reserves have declined significantly during the past several years, pulling down required operating balances. How much further could this process continue? In early 1997, required reserve balances are about \$12 billion, and required clearing balances are about \$7 billion. Suppose that required reserves decline enough in the future that the requirements can be met entirely through vault cash, so that required reserve balances fall to zero. If banks offset about one-quarter of this decline with an increase in required clearing balances, then total required operating balances would fall to \$10 billion. This offset is consistent with recent experience, but other responses are certainly possible in the future. For example, if banks reduced their usage of Federal Reserve priced services, or if the funds rate increased substantially, then banks could pay for all of their priced services with smaller required clearing balances, and they would reduce their balances accordingly. Our simulations assume that the decline in aggregate required operating balances is distributed across banks in proportion to their initial level of required reserve balances.

Table 2 reports the simulated increase in federal funds rate volatility as required operating balances fall toward $10 billion. One critical parameter in the simulations that is especially difficult to pin down is the variability of shocks to clearing demand. The Appendix describes our procedure for estimating the standard deviation of these shocks in 1996 and in 1991. For 1996, we study the behavior of banks that have no required operating balances, and use regression techniques to extrapolate their behavior to all banks; for 1991, we use a slight modification of this procedure. The middle column of the table shows results based on our 1996 estimate, and the right column shows results based on our 1991 estimate.

We begin with our estimate of clearing demand volatility in 1996. The table shows that if required operating balances fell to $10 billion, the daily volatility of the federal funds rate would roughly double. To put this increase in perspective, it would make volatility on an average day about as high as the volatility currently experienced on the last days of maintenance periods. The simulated impact of lower required operating balances is quite non-linear: a drop in balances to $14 billion would elicit only a small increase in funds-rate volatility, but a continued drop below that level would have a much larger effect. This nonlinearity has a straightforward explanation. When a bank's requirement-related demand falls toward its clearing demand, the distributions of shocks to the two curves begin to overlap at an increasing rate. As a result, the probability that the bank's clearing demand will exceed its requirement-related demand on a given day rises at an increasing rate. The accelerating importance of clearing demand causes a corresponding acceleration in funds-rate volatility.

We estimate that the standard deviation of clearing demand shocks was 60 percent larger in 1991 than in 1996. It is quite plausible that clearing demand became less variable between those years, because the Federal Reserve implemented a number of changes that encouraged banks to manage their accounts more closely, and because banks improved their internal operating systems (partly as a result of the Fed's actions). The changes by the Federal Reserve included pricing of daylight overdrafts and improved real-time access to account information through the Fed's Account Balance Monitoring System. If banks can further improve the management of their reserve balances, then clearing-demand variability could decline further in the future, and our simulations would overestimate future funds-rate volatility. But it is also possible that our 1996 estimate is incorrect, and that clearing demand remains about as volatile today as it was in 1991. In this case, a decline in required operating balances to $10 billion would roughly triple the volatility of the funds rate. Once again, the simulations imply that funds-rate volatility would rise gradually at first, and then more dramatically if balances continued to fall.

Why Was Funds-Rate Volatility So High in Early 1991?

The simulations shown in Table 2 predict that required operating balances of $18 billion would lead to a standard deviation of the daily difference between the actual federal funds rate and the intended rate of 22 basis points. Yet, when required operating balances fell to $18 billion in 1991, this measure of funds-rate volatility soared to about 80 basis points. Why was

1991 different?

There are three key factors. First, the average levels of clearing demand were considerably higher in 1991 than they are today. The Appendix describes our technique for estimating individual banks' clearing demands in 1996; this method produces an estimate of aggregate clearing demand of $5.8 billion. But applying the same method to bank data from 1991 produces an estimate of aggregate clearing demand of $9.7 billion. Second, the volatility of clearing demand was much higher in 1991 than in 1996, as we just discussed. These two factors both make it more likely that clearing demands would show through to effective demands with aggregate required operating balances at $18 billion. Moreover, there is a third reason that funds-rate volatility was higher in 1991 than the numbers in Table 2 would suggest. Our simulations assume that the Federal Reserve sets the level of nonborrowed reserves so that the average deviation of the funds rate from the intended rate is zero. But this condition turned out not to hold in early 1991, as the funds rate traded considerably above the intended rate on average. This average positive deviation means that the equilibrium funds rate was more often determined on a steeper portion of the demand curve, which increases volatility.

It is straightforward to produce a new set of simulations based on the higher level and variability of clearing demands in 1991, and on the actual quantity of reserves supplied by the Fed at the time. These simulations predict that the volatility of the federal funds rate with required operating balances of $18 billion would be about 70 basis points--just slightly below the actual experience.

Targeting the Federal Funds Rate With Low Required Operating Balances

A driving force behind our results is that a decline in requirement-related demand makes effective demand less elastic with respect to the federal funds rate. That decline also increases the curvature of the effective demand curve, because it means that more banks will be switching between requirement-related and clearing demand from day to day, and thus moving across the kinks in their effective demand curves. This increased curvature of demand complicates the Federal Reserve's operating procedures.

Our analysis focuses on supply shocks, because demand shocks have completely analogous effects. Suppose that effective demand is linear to start. In this situation, positive and negative supply shocks of equal size have equal effects on the equilibrium federal funds rate. Thus, if shocks are symmetric, and if the Fed aims to supply the quantity of reserves for which the funds-rate deviation equals zero along the effective demand curve, then the average funds-rate deviation will be zero. Now suppose that effective demand is curved, which means that positive supply shocks have less effect on the equilibrium funds rate than negative supply shocks of equal size. Figure 5 shows that if supply shocks are symmetric, and if the Fed follows the same policy as above, then the actual funds rate will exceed its target on average. To make the *expected* funds rate equal to the intended rate, the Fed will need to increase the expected supply of reserve balances.

Another useful way to make the same point is to say that the Fed must provide sufficient reserves to push the *median* funds rate below the intended rate. This phenomenon arises in our simulations. Recall that we set the intended supply of reserves so that the mean funds-rate deviation for a given level of required operating balances was zero. Table 3 shows that the resulting median funds-rate deviations are negative, and are increasingly negative for lower levels of required operating balances. The deviations are nevertheless rather small for our estimate of clearing demand volatility in 1996, although they are quite noticeable for estimated clearing demand volatility in 1991. In this case, with required operating balances at $10 billion, the Fed would need to tolerate the funds rate falling 15 basis points below the intended rate on half of all days in order to hit the intended rate on average.

5. Conclusion

This paper constructs a microeconomic model of the federal funds market and uses it to simulate the behavior of the funds rate in response to declining required reserves. We specify an individual bank's demand for reserve balances as the maximum of its clearing demand and its requirement-related demand. The former represents the bank's demand for balances to avoid overnight overdrafts; the latter represents the bank's demand for balances to meet its reserve and clearing balance requirements. The clearing demand schedule is both steeper and more variable than the requirement-related demand schedule. Thus, when the clearing demand curve becomes "binding" at a larger number of banks, the federal funds rate becomes more volatile.

Our analysis implies that a decline in required operating balances to $10 billion could boost the standard deviation of the daily funds rate around its intended value to about forty basis points. This is roughly double the volatility of the funds rate in recent years, but well below the spike in funds-rate volatility seen in early 1991. The analysis also suggests that little of this increase in volatility would become evident until required operating balances fall below $14 billion.

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Appendix: Parameterizing the Model

We generate parameters for the model using both time-series data on the reserves market and cross-section data on banks. This appendix provides a detailed description of our methods.

Average Levels of Requirement-Related Demand

The aggregate demand for reserve balances depends on the behavior of thousands of institutions that hold accounts at the Federal Reserve. Our simulations incorporate the behavior of all institutions that maintained an active account at the Federal Reserve during the maintenance period running from November 23 through December 6, 1995, and that reported deposit data weekly on the Federal Reserve 2900 report (EDDS). This "base maintenance period" was a prototypical maintenance period, in that aggregate reserve balances were still quite high (around $24 billion), excess reserves were close to their long-run average of $1 billion, and federal funds traded in a narrow range around the intended rate. The 5999 banks in our sample accounted for 97 percent of total required operating balances during the base maintenance period.

Most banks in our sample had a positive required operating balance during the base maintenance period, but some did not. For each bank j in the latter category, the average level of requirement-related demand L_j is identically equal to zero. For each bank in the former category, we set the average level of requirement-related demand equal to the average balance during the base maintenance period. This procedure assumes that clearing demand was not binding for any of these banks on any days during the base maintenance period. While somewhat extreme, the assumption seems plausible in light of the high level of aggregate required balances and the relative stability of the funds rate during the period.

Average Levels of Clearing Demand

For each bank *j* with zero required operating balance during the base maintenance period, we set the average level of clearing demand K_j equal to the average balance during the period. For each bank with a positive required operating balance, we do not observe its underlying clearing demand. Yet, these underlying demands may become binding if required reserves decline, so we need to estimate them. The basic idea is to infer the balances that these banks *would* hold if they had no required balances by modelling the behavior of banks that *currently* have no required balances.[16]

We examine the set of banks that had zero required operating balances during the maintenance periods ending August 28 through September 25, 1996. We use more recent maintenance periods here than for our other estimates in order to maximize the number of institutions--especially larger ones--in the sample. We regress the log of each bank's average reserve balance on the logs of its gross demand deposits and its total deposits; we experimented with including the dollar amounts of each bank's Fedwire transactions, but this term did not enter significantly. Table A1 presents results of separate regressions for large banks (total deposits over $1 billion) and small banks (total deposits under $1 billion). The R^2 of the large-bank regression is about 0.5, although only the coefficient on demand deposits is significant, suggesting that a primary determinant of large-bank clearing demands is activities on behalf of

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[16] We ignore the possibility that clearing demand would respond to changes in funds-rate volatility.

corporate customers, who maintain demand deposits. The R^2 of the small-bank regression is about 0.1, and both demand deposits and total deposits receive coefficients around 0.1 that are statistically significantly different from zero.

We use the estimated coefficients from these regressions to construct an estimate of the average level of clearing demand for each bank with a positive required operating balance during the base maintenance period. As a check on this procedure, we compare these estimated clearing demands with the clearing demands reported by a group of large banks on the Fed's May 1996 Senior Financial Officer Survey (Federal Reserve Board, 1996a).[17] Table A2 shows the results of regressing the reported clearing demands on the estimated demands. The coefficient estimate is around 0.7, and the R^2 of the regression is 0.45.

Interest Elasticities of Demand

Our model of the reserves market employs three semi-elasticities of the demand for reserve balances: the elasticity of requirement-related demand on non-settlement days and on settlement days, and the elasticity of clearing demand on all days. We apply the same elasticities to each bank.

We estimate the elasticity of requirement-related demand using aggregate data for 1993 through 1995, when required balances were fairly high and were thus the dominant part of effective demand. The central problem is identification: an ordinary least squares regression of the quantity of reserves on their price will measure some combination of the supply and demand

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[17] The survey asked banks the minimum level of balances they would like to maintain in their accounts at the close of Fedwire to provide adequate protection against overnight overdrafts. Respondents included fifty large banks, including institutions from each Federal Reserve district.

elasticities. Hamilton (1997) surmounts this problem by noting that flows of funds into the Treasury's account at the Federal Reserve drain reserves from the banking system. Expected flows may be offset by open market operations, but unexpected flows represent exogenous supply shocks. Hamilton estimates that an unexpected flow into the Treasury account of $1 billion reduces the quantity of reserves by $420 million and raises the funds rate by 8.8 basis points if it occurs on a settlement day and by 0.3 basis points if it occurs on a non-settlement day.[18] The average level of reserve balances during Hamilton's 1989-91 sample period was $29.0 billion, so the hypothesized shock represents a 1.45 percent decline in balances (420/29000). The implied semi-elasticities of reserve demand are then 0.16 on settlement days (.0145/.088) and 4.83 on non-settlement days (.0145/.003).

We modify Hamilton's procedure to produce our own elasticity estimates. Note that Hamilton did not have access to the Federal Reserve's actual forecasting errors for the Treasury balance, so he constructed expected and unexpected changes in the balance using a time series model that he developed in an earlier paper (Hamilton, 1996). We substitute the actual Fed forecasts over the 1993-95 period. Our specification follows Hamilton's choice of additional explanatory variables quite closely, but is estimated using ordinary least squares rather than the conditional variance techniques that Hamilton used. The results are reported in Tables A3 and A4. We find that an unexpected flow of $1 billion into the Treasury account reduces the quantity of reserves by $880 million. Because there is no reason that this effect should not be one-for-one, our estimate is much more plausible than Hamilton's. We also find that such a

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[18] These estimates are reported in Hamilton's Tables 3 and 4. The effect on the funds rate for non-settlement days represents the average of Hamilton's estimated effects for the first nine days of a maintenance period.

shock would raise the funds rate by 10.1 basis points on a settlement day and 1.8 basis points on a non-settlement day. With an average level of reserve balances during our sample period of $24.5 billion, these estimates imply semi-elasticities of 0.36 and 2.00.

Unfortunately, this difference in elasticities implies a greater difference between the simulated volatility of the funds rate on settlement days and non-settlement days than is actually the case. Therefore, our simulations are based on a semi-elasticity of 0.4 for settlement days and 1.3 for non-settlement days. Even this reduced elasticity for non-settlement days implies that if required operating balances were $20 billion, banks would be willing to hold $70 billion in additional balances when the funds rate falls one percentage point below its target.

We could devise no way to make a sensible estimate of the elasticity of clearing demand. For example, regressing the log of aggregate daily balances held by banks with zero required balances on the federal funds rate yields a *positive* but statistically insignificant coefficient. The actual elasticity is obviously negative, but should be quite close to zero: both the very high funds rates that are occasionally observed and anecdotal information from reserves managers confirm that banks have few alternatives when they need reserve balances for clearing purposes. In fact, the elasticity should be smaller than the elasticity of requirement-related demand on settlement days, because carryover provisions provide banks with some scope for substituting required reserve balances and required clearing balances across maintenance periods. Therefore, we choose an elasticity of clearing demand equal to 0.1.

Demand Shocks

The model includes shocks to both requirement-related demand and clearing demand. The shocks are aggregate, or common, shocks because they have the same proportional effects on all banks. We draw the shocks to requirement-related demand from a lognormal distribution with volatility parameter set at 0.155; that is, the standard deviation of the log of the shocks is 0.155. This value is chosen *contingent* upon the other parameters in the model so that the simulated volatility of the federal funds rate at high levels of required operating balances matches the observed volatility for 1993 through 1995.

Determining the size of the shocks to clearing demand is more complicated. We take all banks that had zero required operating balance during the maintenance periods ending August 28 through September 25, 1996, and divide them into groups based on the amount of their total deposits. The size classes (in millions of dollars) are: less than 200, 200-400, 400-600, 600-800, 800 to 1000, 1000-2000, 2000-10,000, 10,000-20,000, and over 20,000. We sum the reserve balances of the banks in each group on each day, and calculate the variance of the log of each series over the sample period.[19] Then we regress the log of the calculated variance on the log of the average level of deposits across size groups, finding that large banks have proportionally more variable clearing demands than small banks. We use the estimated coefficient from this regression to project the variance of clearing demand for all 5999 banks in our model. Finally, we weight these variances by banks' average clearing demands to produce an estimated variance of aggregate clearing demand. Our estimate of 0.297 is almost double the volatility of requirement-related demand.

For comparison, we make a similar calculation for early 1991. Despite the sharp decline

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[19] The variability in actual end-of-day balances slightly overstates the variability in desired balances because the end-of-day balance includes late-day shocks that the bank does not offset.

in required reserves, most institutions still faced positive required reserve balances. One way to identify banks whose effective demands for reserve balances were driven primarily by their clearing demands is to note that such banks would have held balances well in excess of their requirements. Therefore, we apply the methodology described in the previous paragraph to the set of banks whose excess reserves in early 1991 were more than three times their excess reserves in late 1990. The resulting estimate of the volatility of clearing demand in early 1991 is 0.489.

Supply Shocks

Our model specifies the supply of reserve balances as the sum of the Federal Reserve's intended supply and a supply shock. These supply shocks arise from a number of factors beyond the Fed's direct control that change the supply of reserves each day, including changes in the amount of cash that banks wish to hold and flows of funds into the Treasury's account at the Fed. The Fed makes daily forecasts of these factors and uses this information in determining its open market operations. On a day when the Fed conducts an open market operation, the error in this forecast is a good measure of the supply shock. Because the Fed always intervenes on settlement days, we draw supply shocks for those days from a normal distribution with standard deviation equal to \$1.15 billion, which is the standard deviation of the Fed's forecast errors over the 1993-95 period.

On a day when the Fed does not enter the reserves market, it is more difficult to ascertain the supply shock. One reasonable approximation is the difference in the supply of reserves from its average value on neighboring days. Because there is sometimes a deliberate increase in reserves late in a maintenance period, we calculate the standard deviation of reserves over the first seven days of each maintenance period. The mean value of these deviations was $2.8 billion in 1993, somewhat lower in 1994-95, and then above $3 billion in early 1996. Note that the Fed intervenes on some non-settlement days but not on others, and we do not separate these days in our estimates. Instead, we simply draw supply shocks for all non-settlement days from a normal distribution with standard deviation equal to $2.8 billion.

Table 1
Parameters of the Model

Parameter	Value	Source of Estimate
Average levels of requirement-related demand (L_j's)	--	Cross-section regressions on individual bank data
Average levels of clearing demand (K_j's)	--	Cross-section regressions on individual bank data
Interest semi-elasticity of requirement-related demand (α)		
settlement days	0.4	Aggregate time series estimate
non-settlement days	1.3	Aggregate time series estimate adjusted to match observed funds-rate volatility on settlement vs. non-settlement days
Interest semi-elasticity of clearing demand (β)	0.1	Prior belief that it should be smaller than α on settlement days
Standard deviation of shocks to requirement-related demand (σ_u)	0.155	Chosen to match observed funds-rate volatility in 1993-95
Standard deviation of shocks to clearing demand (σ_v)	0.297	Cross-section regressions using individual bank data
Intended supply of reserves (A)	--	Chosen to make average simulated funds-rate deviation equal to zero
Standard deviation of shocks to supply (σ_w)		
settlement days	1150	Time series data
non-settlement days	2800	Time series data

Table 2
Simulated Volatility of the Federal Funds Rate

Required Operating Balances ($ billions)	Standard Deviation of the Daily Difference Between the Actual and Intended Rates (basis points)	
	Estimated Clearing Demand Volatility in 1996 (σ_u = 0.297)	Estimated Clearing Demand Volatility in 1991 (σ_u = 0.488)
20	21	24
18	22	28
16	23	36
14	25	46
12	30	60
10	41	76

Table 3
Simulated Median Deviation of the Federal Funds Rate from Target

Required Operating Balances ($ billions)	Median Daily Difference Between the Actual and Intended Rates (basis points)	
	Estimated Clearing Demand Volatility in 1996 (σ_u = 0.297)	Estimated Clearing Demand Volatility in 1991 (σ_u = 0.488)
20	-2	-1
18	-2	-2
16	-2	-4
14	-2	-6
12	-2	-10
10	-5	-15

Table A1
Determinants of Clearing Demand

Dependent variable equals log(balances) at banks with zero required balances

Independent Variable	Estimated Coefficient (t-statistic in parentheses)	
	Small Banks	Large Banks
constant	-3.46 (-22.2)	-4.41 (-0.8)
log(gross demand deposits)	0.13 (3.5)	0.54 (3.3)
log(total deposits)	0.10 (2.4)	0.25 (0.3)
number of observations	494	17
R^2	0.08	0.47

Table A2
Comparison of Estimated Clearing Demands with Reported Values

Dependent variable equals reported clearing demand

Independent Variable	Estimated Coefficient (t-statistic in parentheses)
constant	5.3 (1.2)
estimated clearing demand	0.71 (6.2)
number of observations	49
R^2	0.45

Note: Reported demands are from the Federal Reserve's May 1996 Senior Financial Officer Survey; estimated demands are based on estimated coefficients in Table A1.

Table A3
Effect of Federal Reserve Forecast Errors on Reserve Supply

Dependent variable equals nonborrowed reserves

Independent Variable	Estimated Coefficient (t-statistic in parentheses)
forecast error of the Treasury balance at the Federal Reserve	-0.88 (-7.8)
number of observations	579
R^2	0.43

Note: Sample is weekdays from 1993 through 1995 excluding holidays. The regression also includes a constant, lagged values of nonborrowed reserves and changes in the funds rate, dummy variables for each month and for the first and last day of a maintenance period, and variables interacting the first day of a period and lagged values of reserves and changes in the funds rate. This list closely follows Hamilton (1997).

Table A4
Effect of Federal Reserve Forecast Errors on the Federal Funds Rate

Dependent variable equals the change in the funds rate

Independent Variable	Estimated Coefficient (t-statistic in parentheses)
forecast error of the Treasury balance at the Federal Reserve	
on settlement days	.101 (5.7)
on non-settlement days	.018 (2.0)
number of observations	701
R^2	0.46

Note: Sample is the same as in Table A3, but there are more useable observations here because there are no lagged independent variables. The regression also includes a constant, the predicted Treasury balance at the Federal Reserve, and dummy variables for days before and after holidays and for each day of a maintenance period. This list closely follows Hamilton (1997).

Figure 1

Required Balances at Federal Reserve Banks

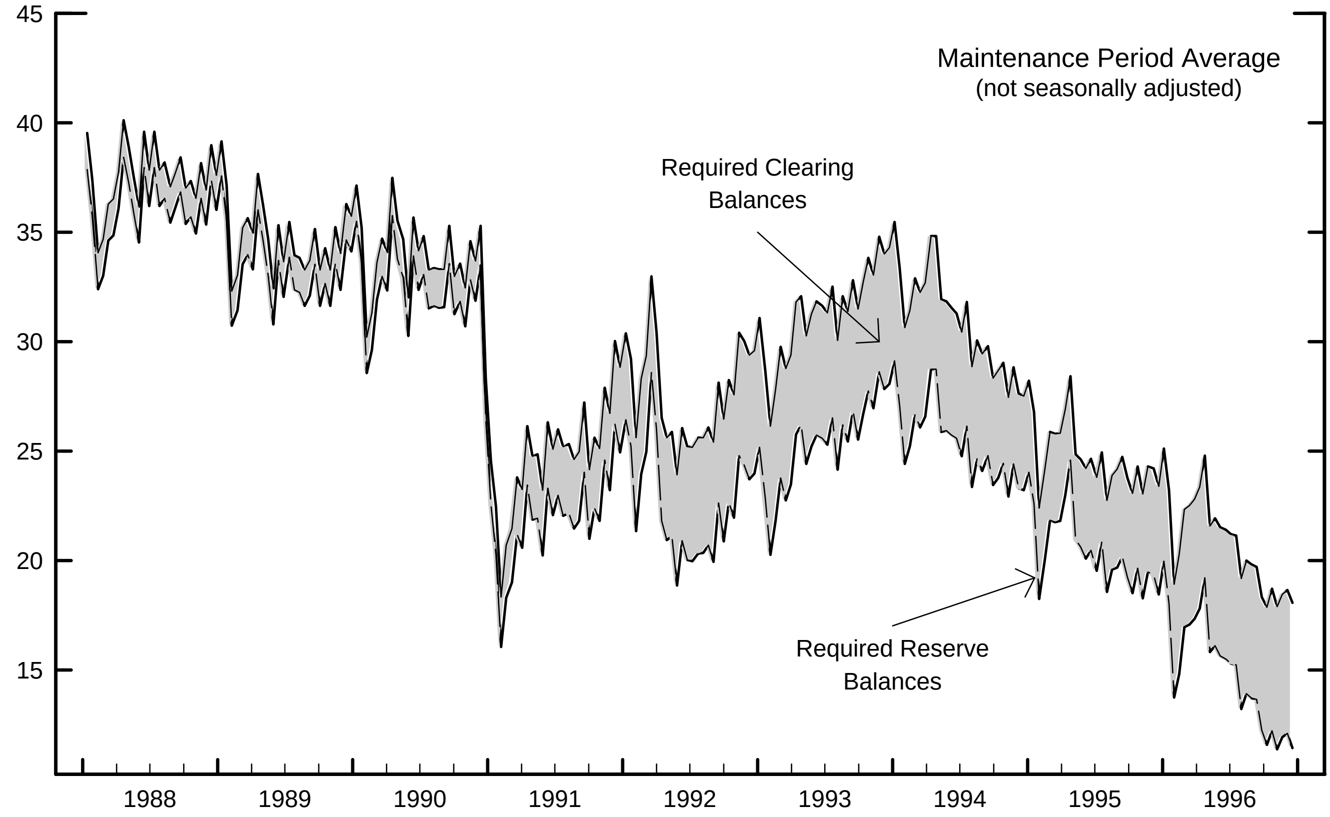


Figure 2

Standard Deviation of Daily Difference Between Actual Federal Funds Rate and Intended Rate

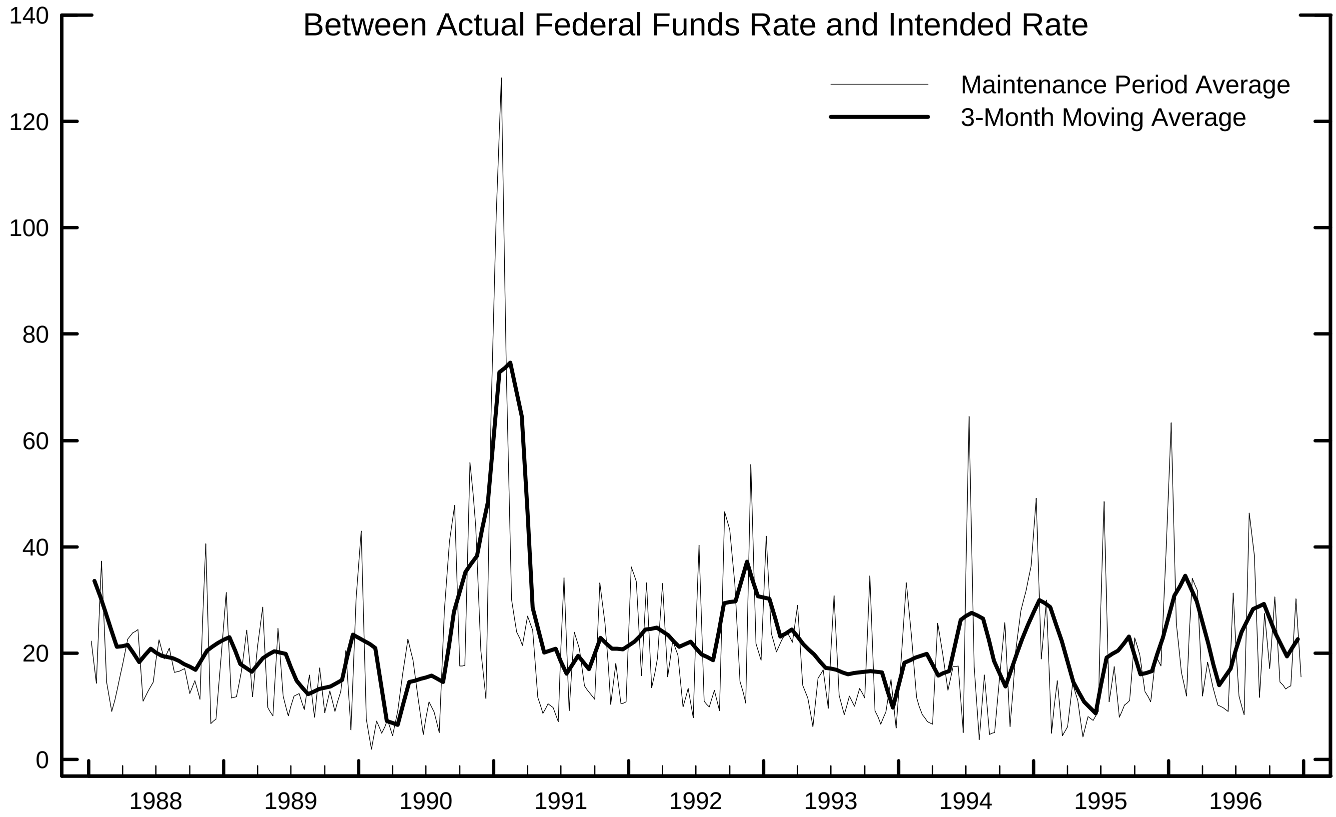


Figure 3

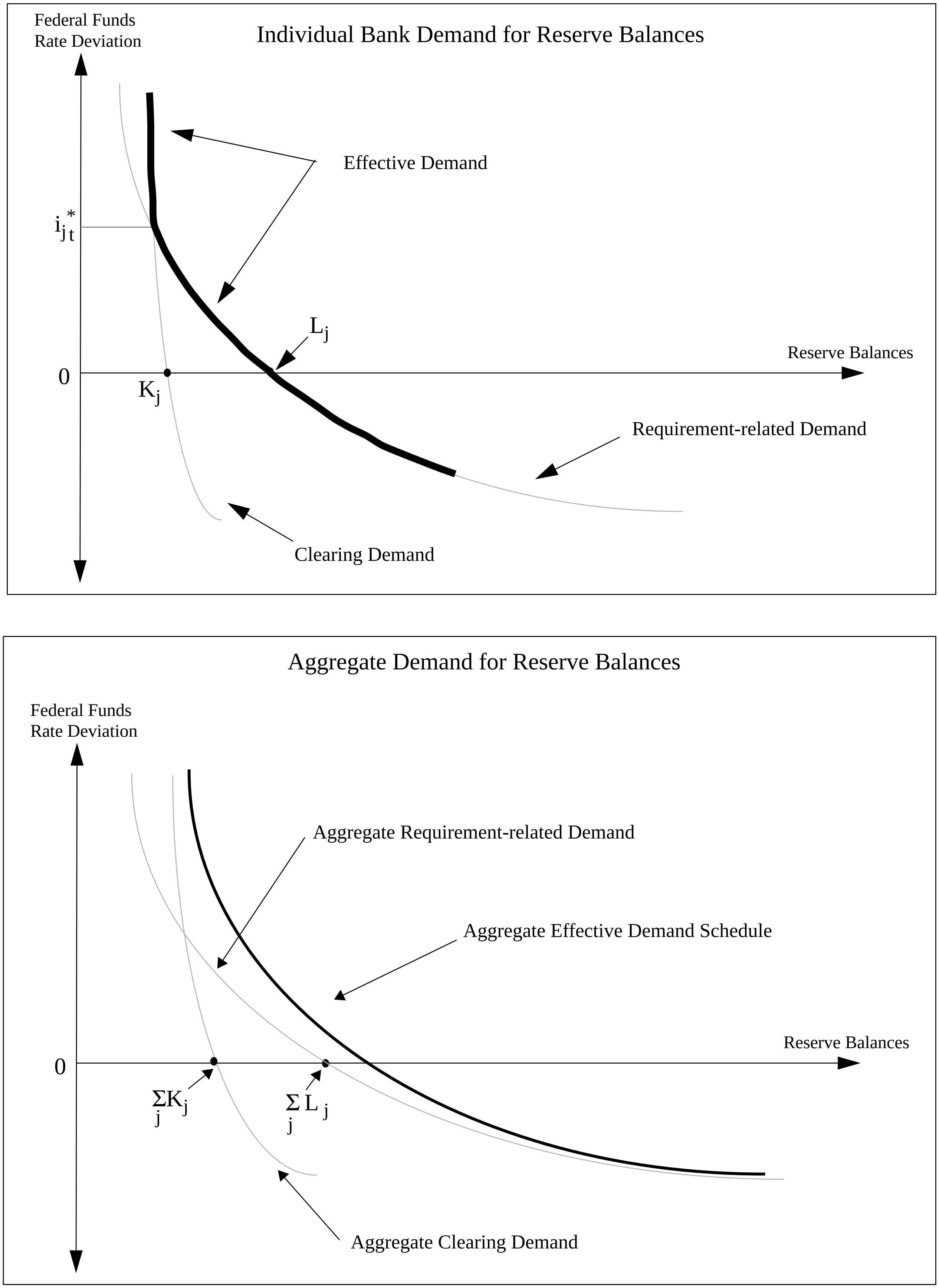
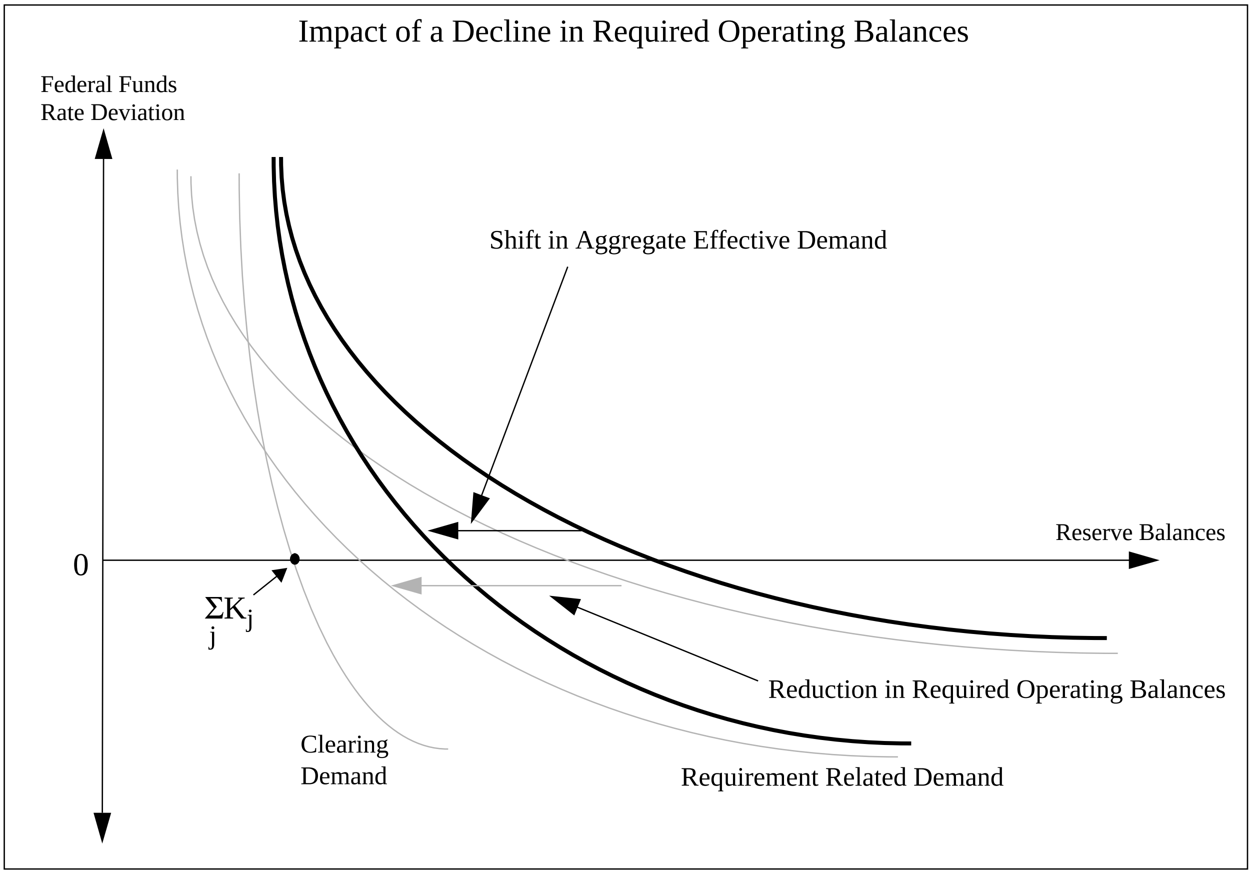

Individual Bank Demand for Reserve Balances
Federal Funds
Rate Deviation
Effective Demand
i_{jt}^{*}
L_j
Reserve Balances
0
K_j
Requirement-related Demand
Clearing Demand
Aggregate Demand for Reserve Balances
Federal Funds
Rate Deviation
Aggregate Requirement-related Demand
Aggregate Effective Demand Schedule
Reserve Balances
0
$\sum_j K_j$
$\sum_j L_j$
Aggregate Clearing Demand

Figure 4


Impact of a Decline in Required Operating Balances

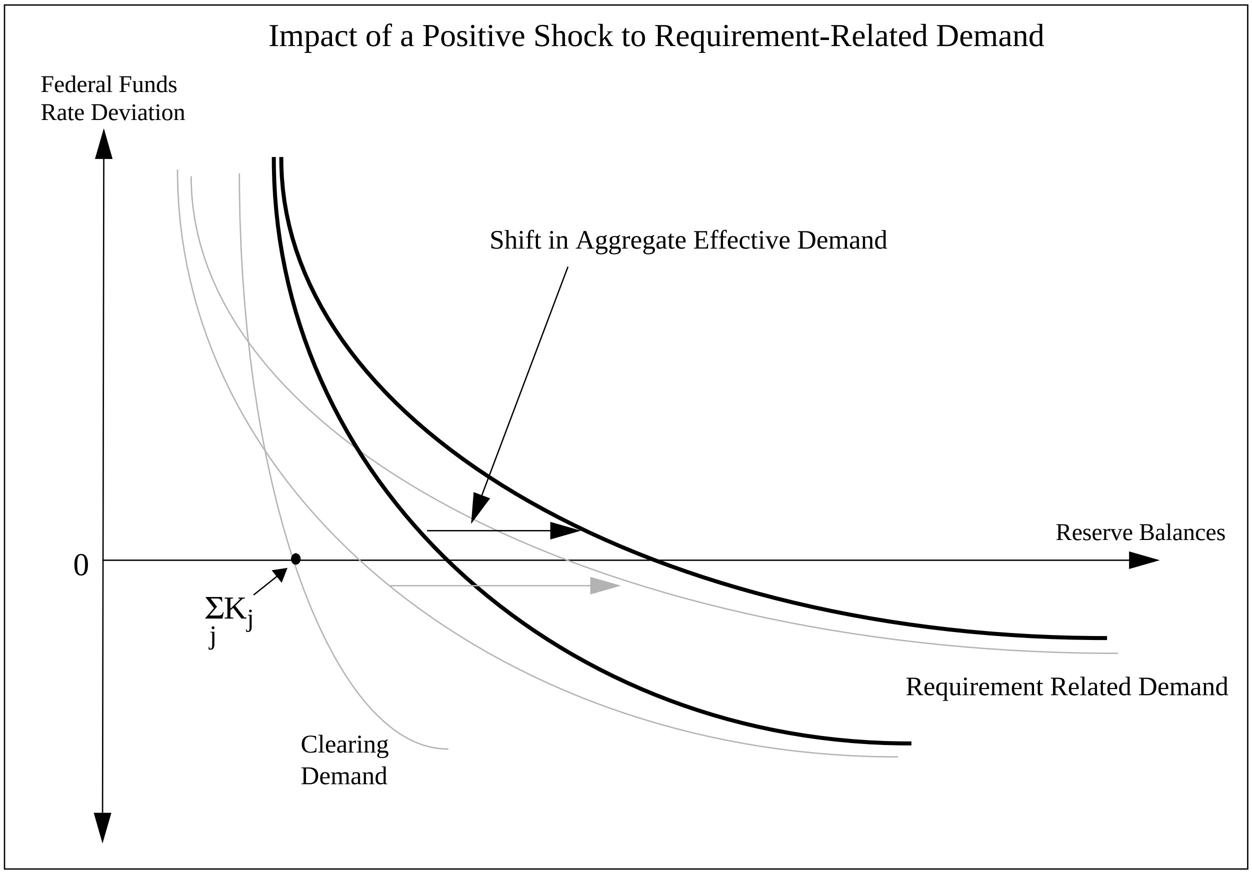
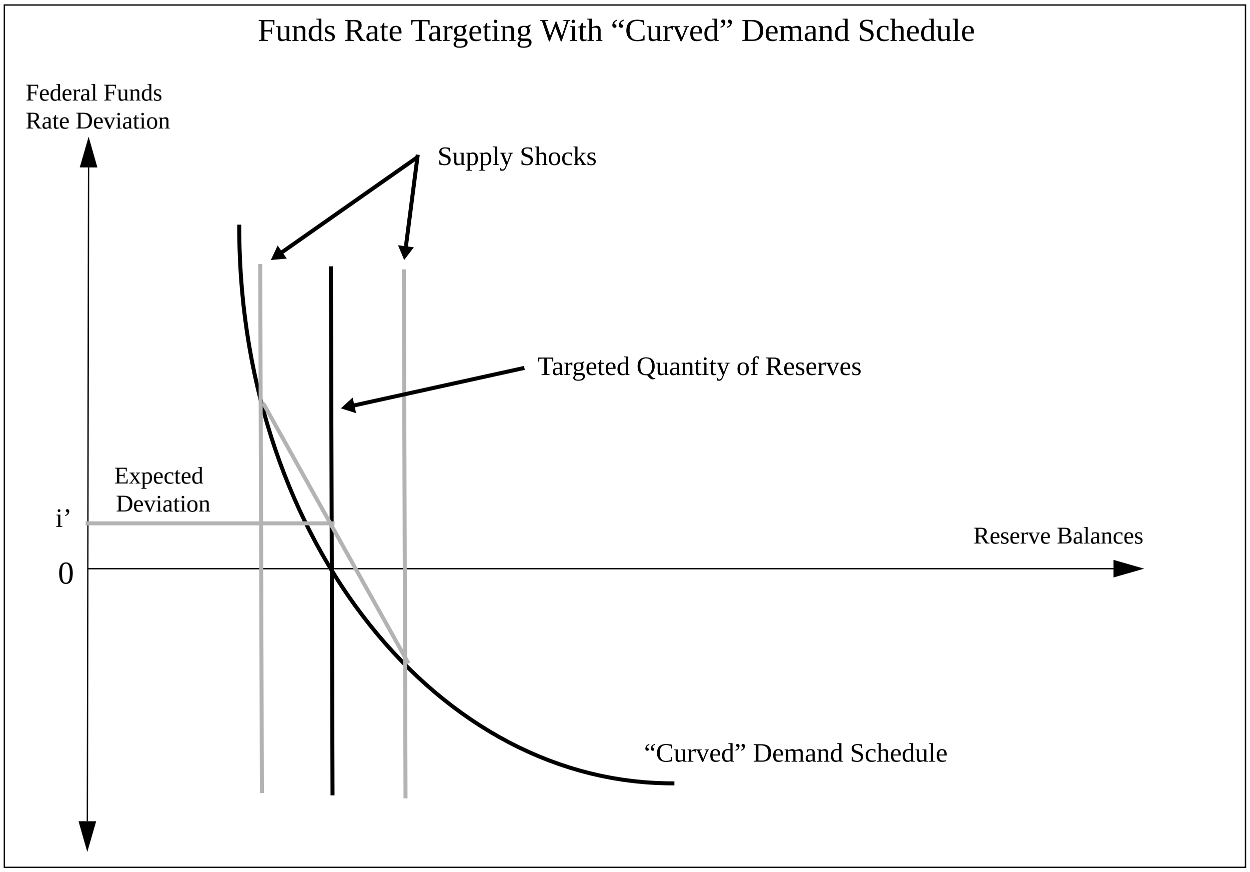

Impact of a Positive Shock to Requirement-Related Demand

Figure 5


Funds Rate Targeting With “Curved” Demand Schedule
Federal Funds
Rate Deviation
Supply Shocks
Targeted Quantity of Reserves
Expected
Deviation
i’
0
Reserve Balances
“Curved” Demand Schedule