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ECB WORKSHOP
ON THE ANALYSIS OF
THE MONEY MARKET

WORKING PAPER SERIES
NO 984 / DECEMBER 2008

THE DAILY AND POLICY-RELEVANT LIQUIDITY EFFECTS

by Daniel L. Thornton

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ECB WORKSHOP ON THE ANALYSIS OF THE MONEY MARKET

On 14 and 15 November 2007, Alain Durré, Huw Pill and Diego Rodriguez-Palenzuela of the ECB's Monetary Policy Stance Division organised a central bank workshop titled "The Analysis of the Money Market: Role, Challenges and Implications from the Monetary Policy Perspective". This workshop provided an opportunity for participating central bank experts to exchange views and foster debate, also in interaction with international organizations and academic institutions. The first day of the workshop addressed issues related to the macro-perspective of the money market, drawing on the experiences of a large number of countries. The second day adopted a micro-perspective on the money market, looking in particular at trading behaviour in the overnight money market and its implications for the evolution of spreads.

A first version of this paper was presented at this workshop. The papers presented at the time of the workshop did not consider the potential implications of the financial turmoil for the results of the paper, given that the tensions in money markets emerged in August 2007. The published version of these papers represents an update of the original paper, which incorporates the discussion which took place at the workshop and in most cases a discussion on the developments in the money markets since August 2007.

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Abstract

The phrase "liquidity effect" was introduced by Milton Friedman (1969) to describe the first of three effects on interest rates caused by an exogenous change in the money supply. The lack of empirical support for the liquidity effect using monthly and quarterly data using various monetary and reserve aggregates led Hamilton (1997) to suggest that more convincing evidence of the liquidity effect could be obtained using daily data – the daily liquidity effect. This paper investigates the implications of the daily liquidity effect for Friedman's liquidity effect using a comprehensive model of the Fed's daily operating procedure. The evidence indicates that it is no easier to find convincing evidence of a Friedman's liquidity effect using daily data than it has been using lower frequency data.

Keywords: liquidity effect, federal funds rate, monetary policy, operating procedure, FOMC

JEL Classification: E40, E52

Non-technical summary

The phrase "liquidity effect" was introduced by Milton Friedman (1969) to describe the first of three effects on interest rates caused by an exogenous change in the money supply. Specifically, it is the idea that, all other things the same, an increase in the supply of credit due to a Federal Reserve engineered change in the money supply would initially cause interest rates to fall. Despite the widespread belief that the Fed and other central banks can control interest rates by altering the supply of credit in the market researchers were unable to find empirical evidence of a statistically significant and economically relevant liquidity effect using a variety of monetary and reserve aggregates using monthly or quarterly data. The failure to find empirical evidence of the liquidity effect was attributed to a variety of technical issues associated with the tests that were commonly used. Jim Hamilton (1997) suggested that one could obtain an estimate of the liquidity effect by estimating the liquidity effect using daily data, i.e., by estimating the "daily liquidity effect." Specifically, Hamilton estimated the response of the federal funds rate to shocks to the supply of reserves that he estimated with a model of the Treasury's balance at the Fed. Thornton (2001) noted that the forecast errors that Hamilton estimated were not necessarily the same as the forecast errors that the Fed made each day in implementing monetary policy. Hence, the fact that the actual change in the interest rate was negatively correlated with his forecast errors could not be taken as evidence of a daily liquidity effect. Thornton also noted that Hamilton only found evidence of the daily liquidity effect on "settlement Wednesday"—the day when the federal funds rate is more volatile because banks have to meet their reserve requirements. Subsequent analyses by Carpenter and Demiralp (2006) and Thornton (2007) investigate these aspects of Thornton's analysis is more detail.

The current paper extends the literature on the daily liquidity effect by showing exactly what conditions have to be met in order for evidence of a daily liquidity effect to be considered as evidence of the liquidity effect defined by Friedman—the policy-relevant liquidity effect. Specifically, I show that the daily liquidity effect is directly linked to the Friedman's policy-relevant liquidity effect by reserve requirements that the Fed imposes on banks. I then use a detailed model of the Fed's daily operating procedure to (1) estimate the daily liquidity effect and (2) to analyze the effect of specific aspects of the Fed's reserve requirements, and changes in reserve requirements over time, on the relationship between the daily and policy-relevant liquidity effects.

Estimates of the model using data before 1994 suggest that there may have been a statistically significant policy-relevant liquidity effect. The estimated daily liquidity effect is small—it would take a $10 billion reserve supply shock to generate about a 20-basis-point change in the funds rate. Given that the average effective reserve requirement during this period was about 10 percent, a $10 billion reserve supply shock would be equivalent to a $100 billion shock in the money supply. Such a shock would be extremely large historically. Beginning in 1994 a large number of banks began sweeping deposits that were subject to reserve requirements into deposits that were not. These so-called sweep accounts effectively eliminated reserve requirements for a large number of banks. In addition, in July 1998 the Fed virtually eliminated any relationship between the daily

and policy-relevant liquidity effects by reinstating lagged reserve accounting. There is still a statistically significant daily liquidity effect after 1998 owing to the fact that reserve demand is interest sensitive even if there is no contemporaneous relationship between reserve demand and money demand. However, estimates of a statistically significant daily liquidity effect after July 1998, reported here and elsewhere, have no implications for the policy-relevant liquidity effect. The analysis presented here suggests that it is no easier to find convincing proof of a statistically significant and economically important policy-relevant liquidity effect using high-frequency daily data than it has been using lower frequency (monthly and quarterly) data. A resolution of the liquidity puzzle remains elusive.

1. Introduction

The phrase "liquidity effect" was first used by Milton Friedman (1969) to describe the first of three effects on interest rates caused by an exogenous change in the supply of money.[1] I refer to Friedman's liquidity effect as the policy-relevant liquidity effect. Despite its prominent role in conventional theories of the monetary policy transmission mechanism, there has been very little evidence of a statistically significant or economically meaningful liquidity effect.[2] Suggesting that previous attempts to identify the liquidity effect have been unsuccessful because low frequency data necessarily mixes together the effects of policy on economic variables with the effects of economic variables on policy, Hamilton (1997) sought to develop a "more convincing measure of the liquidity effect" by estimating the response of the federal funds rate to exogenous reserve supply shocks using daily data, i.e., by estimating the daily liquidity effect. Thornton (2001a) showed that the estimated daily liquidity effect that Hamilton reported was the consequence of a few extreme observations and that there was no evidence of a daily liquidity effect using Hamilton's model and methodology for sample periods prior to and after Hamilton's. Recently, Carpenter and Demiralp (2006) report evidence of a daily liquidity effect using a more complete model of the operating procedure of the Trading Desk of the Federal Reserve Bank of New York (hereafter, Desk) than that used by Hamilton and using a reserve supply shock measure that more adequately reflects reserve supply shocks that occur each day in conduct of open market operations.

[1] The other two are called the "income" and "price expectation" or "inflation expectation" effects (e.g., Friedman, 1969; and Gibson, 1970a,b). These effects have roots in classical economics (e.g., Humphrey, 1983a,b). Because of the inflation expectation effect, an exogenous change in money growth eventually leads to higher, rather than lower, equilibrium nominal interest rates.

[2] The empirical literature on the liquidity effect dates back at least to Cagan and Gandolfi (1969) and Gibson (1970a,b).

While they Carpenter and Demiralp (2006) claim their results have implications for the policy-relevant liquidity effect, neither their model nor Hamilton's (1997) explicitly models the structural relationship that link the daily and policy-relevant liquidity effects. This paper fills this gap by analyzing the relationship between the daily and policy-relevant liquidity effects using a comprehensive model of the Desk's operating procedure. The analysis shows that because of specific features in the Desk's operating procedure, the Fed's system of reserve requirements, and other factors, the relationship between the daily liquidity effect and the policy-relevant liquidity effect is neither simple nor direct.

The model is estimated using Carpenter and Demiralp's reserve shock measure. The empirical evidence suggests that it is no easier to find convincing evidence of a policy-relevant liquidity effect using high-frequency daily data than it has been using monetary and reserve aggregates at the monthly or quarterly frequencies.

The remainder of the paper is divided into three sections. Section 2 investigates the relationship between the daily liquidity effect and the liquidity effect relevant for monetary policy using a detailed model of the Desk's operating procedure. Section 3 estimates the model developed in Section 2 using daily data and Carpenter and Demiralp's reserve supply shock measure. The conclusions are presented in Section 4.

2. The Policy-Relevant and Daily Liquidity Effects

Milton Friedman (1969) termed the first of three effects of an exogenous change in the supply of money on nominal interest rates the "liquidity effect." Friedman's liquidity effect is what economists have in mind when they discuss the liquidity effect. Hence, this is the liquidity effect that is relevant for monetary policy, i.e., the policy-

relevant liquidity effect. The policy-relevant liquidity effect stems directly from the demand for money, i.e.,

(1) $$M_t^d = f(i_t, y_t),$$

where M_t^d denotes the demand for money, which, for purposes of illustration, is a simple function of a nominal interest rate, i_t, and nominal income, y_t. Because individuals economize on their holding of money when interest rates rise, $\partial f / \partial i < 0$.

Equilibrium requires that the supply of money, M_t^s (which, for simplicity, is assumed to be exogenously controlled by the Fed) equals demand, i.e.,

(2) $$M_t^s = f(i_t, y_t).$$

The policy-relevant liquidity effect is the initial effect of an exogenous change in the money supply on the interest rates and is given by

(3) $$di_t / dM^s = (\partial f / \partial i)^{-1},$$

where it is assumed that neither nominal income nor inflation expectations respond immediately to the Fed's actions. Friedman (1969) called (3) the "liquidity effect."

Vast empirical evidence indicates that the demand for money is negatively related to the interest rate and is interest inelastic. This implies that a small exogenous change in the supply of money should cause a relatively large response in interest rates. That is, the policy-relevant liquidity effect should be relatively large and statistically significant. Consequently, the inability of researchers to find a statistically significant and economically meaningful liquidity effect is referred to as the "liquidity puzzle."[3]

Among other things, the failure to find evidence of the liquidity effect using low

[3] See Strongin (1995).

frequency monetary and reserve aggregates has been attributed to the response of nominal income or inflation expectations to money supply shocks or to the inability of researchers to isolate exogenous monetary shocks. Researchers have attempted to overcome these problems using, among other things, structural vector autoregressions (SVARs). The recursive SVAR, or RSVAR, has been particularly popular in this literature. SVAR models have been estimated using a variety of monetary and reserve aggregates. Pagan and Robertson (1995) show that it is difficult to find convincing evidence of a liquidity effect with these models.[4]

The failure of researchers to generate evidence of a statistically significant and empirically relevant liquidity effect using monthly or quarterly data led Hamilton (1997) to suggest that the failure of the RSVAR approach likely stems from the fact that it "claims to uncover…innovations in Fed policy, defined as a change in a policy variable that is deliberately induced by Federal Reserve actions that could not have been anticipated on the basis of earlier available information." Hamilton suggested that changes in Fed policy are frequently due to information about "current or future values of output, inflation, exchanges rate, or other magnitudes," so that "the correlation between such a 'policy innovation' and the future level of output of necessity mixes together the effect of policy on output with the effect of output forecasts on policy."[5] He suggested that the liquidity effect could be more easily identified by estimating the response of the

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[4] The exception is using RSVAR with nonborrowed reserves as the monetary aggregate. Coleman, Gilles and Labadie (1996) pointed out, however, that evidence of a liquidity effect using nonborrowed reserves may be a consequence of the Desk's efforts to offset the effect of changes in discount window borrowing. Thornton (2001b) confirmed this by showing that the estimated liquidity effect using nonborrowed reserves is a consequence of the interest sensitivity of discount window borrowing and Desk's operating procedure under either monetary aggregate or funds rate targeting. He shows that this "liquidity effect" using nonborrowed reserves vanishes in the early 1980s when borrowing declined dramatically and became relatively interest insensitive.

[5] Hamilton (1997), p. 80.

funds rate reserve supply shocks measured at the daily frequency. Specifically, he estimated reserve supply shocks from a simple time-series model of the Treasury's daily deposits at the Fed. Assuming that the errors from this model proxy the reserve supply shocks that the Trading Desk of the Federal Reserve Bank of New York (hereafter, Desk) makes each day in conducting open market operations, Hamilton (1997) estimated the response of the federal funds rate to his estimated reserve supply shocks. He referred to this as the daily liquidity effect.

2.1 The Relationship between the Policy-Relevant and Daily Liquidity Effects

The relationship between the policy-relevant liquidity effect and Hamilton's daily liquidity effect is a consequence of the fact that the Fed imposes reserve requirements on components of money. This creates a direct link between the demand for money—the source of Friedman's liquidity effect—and the demand for reserves—the source of the daily liquidity effect. That is,

(4) $$R_t^d = rrM_t^d = rrf(i_t, y_t),$$

where R_t^d denotes reserve demand and rr denotes the Federal-Reserve-imposed percentage reserve requirement. Because of (4), it is possible to estimate the policy-relevant liquidity effect by estimating the response of interest rates to an exogenous change in the supply of reserves—the daily liquidity effect. Moreover, since the response will be identical whether the shock to reserves is due to an error the Desk makes in conducting daily open market operations or is monetary policy-induced exogenous shock to reserves, the there is no identification problem as there is using higher level monetary aggregates. It is sufficient to identify a shock to reserve supply from any source.

It is clear from equation (4) that the relationship between the daily and policy-

relevant liquidity effects depends on the Desk's daily operating procedure, which has remained essentially the same since at least the early 1970s and the Fed's system of reserve requirements, which has not.

The analysis begins with a model of the Desk's operating procedure. Each day the Desk estimates the quantity of reserves that banks will demand over a maintenance period ending every other Wednesday, called settlement Wednesday.[6] The Desk also estimates the quantity of reserves that will be supplied if the Desk conducts no open market operations that day.[7] If the former estimate exceeds the latter, the operating procedure suggests that the Desk add reserves through an open market purchase. If the former is smaller than the latter, the procedure suggests that reserves be drained through an open market sale.

Specifically, the Desk estimates the demand for total reserves, i.e.,

(5) $$E_{t-1}TR_t^d = E_{t-1}rrf(i_t, y_t) + E_{t-1}ER_t^d ,$$

where TR_t^d denotes the demand for total reserves derived from the demand for money, ER_t^d denotes depository institutions' demand for excess reserves, and E_{t-1} denotes the expectation operator conditional on information available before that day's open market operation.

The supply of reserves available each day is given by

(6) $$TR_t^s = B_t + BR_t + F_t + OMO_t ,$$

[6] Until October 1979 the estimate of demand was conditional on the objective or target for the federal funds rate. From October 1979 to September 1982, the estimate was conditional on the objective for the growth rate of the M1 monetary aggregate. Beginning in September 1982, the Fed claimed that the estimate was conditional on an objective for borrowed reserves; however, Thornton (2006) provides evidence from FOMC transcripts suggesting that the real objective was the federal funds rate. Today the objective is unquestionably the federal funds rate.
[7] A more detailed analysis of the Desk's operating procedure can be found in Feinman (1993) and Thornton (2001b, 2007).

where B_t denotes the Fed's holding of government debt prior to that day's open market operation, BR_t denotes bank borrowing at the discount window, F_t denotes autonomous factors that affect reserve supply—currency in circulation, the Treasury's balance at the Fed, the float, etc.—and OMO_t denotes the amount of open market purchases or sales conducted by the Desk that day.[8]

Each day the Desk estimates the supply of reserves that will be available if the Desk conducts no open market operations, i.e, $OMO_t = 0$. The Desk essentially knows the magnitude of B_t, but must make an estimate the F_t. The Desk does not estimate borrowing, but rather applies the Federal Open Market Committee (FOMC) determined borrowing assumption, called the initial borrowing assumption (IBA_t).[9] The estimate of reserve supply if the Desk conducts no open market operations is

$$(7) \qquad E_{t-1}TR_t^s = B_t + E_{t-1}F_t + IBA_t ,$$

where $E_{t-1}F_t$ denotes the Desk's estimate of autonomous factors. The amount of the open market operations suggested by the Desk's operating procedure—the operating procedure-determined open market operation ($OPDOMO_t$)—is given by

$$(8) \qquad OPDOMO_t = (E_{t-1}rrf(i_t, y_t) + E_{t-1}ER_t^d) - (B_t + E_{t-1}F_t + IBA_t) .$$

If $OPDOMO_t$ is positive, the procedure directs the Desk to purchase government securities; if it is negative, the procedure indicates that securities should be sold.

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[8] Borrowing (and later the initial borrowing assumption) refers to seasonal plus adjustment borrowing. Extended credit borrowing is treated separately, as one of the autonomous factors affecting reserve supply.
[9] The *IBA* was changed relatively infrequently and, most often, when the funds rate target was changed. Thornton (2006) shows that the *IBA* was last mentioned in discussing monetary policy during a conference call on January 9, 1991. However, it remained part of the Desk's formal operating procedure until at least 1996.

If the Desk followed its operating procedure exactly, $OMO_t = OPDOMO_t$. The operating procedure is intended to provide the Desk guidance, however. Judgment is used to conduct each day's open market operation. Indeed, over most of the period examined here, the Desk almost never followed the operating procedure exactly (e.g., Thornton, 2007). To allow for this fact, let

(9) $$OMO_t = OPDOMO_t + k_t ,$$

where k_t denotes the amount by which actual open market operations differ from the open market operations recommended by the operating procedure.

Reserve market equilibrium requires that the demand for reserves equals the supply, i.e.,

(10) $$rrf(i_t, y_t) + ER_t^d = B_t + F_t + BR_t + OMO_t .$$

Substituting (8) and (9) into (10) yields

(11) $$rrf(i_t, y_t) = E_{t-1}rrf(i_t, y_t) - (ER_t^d - E_{t-1}ER_t^d) - (F_t - E_{t-1}F_t) - (BR_t - IBA_t) + k_t .$$

The interest rate that equates the reserve market is the federal funds rate, ff_t, which the FOMC has been targeting since 1982.[10] Consequently, the Desk's expectation of reserve demand is conditional on the FOMC's target for the funds rate. Consequently, (11) can be rewritten as

(12) $$rrf(ff_t, y_t) = rrE_{t-1}f(ff_t^*, y_t) - (ER_t^d - E_{t-1}ER_t^d) - (F_t - E_{t-1}F_t) - (BR_t - IBA_t) + k_t .$$

The daily liquidity effect is given by

[10] See Thornton (1988, 2006) for the relevant evidence.

(13) $$\frac{\partial ff_t}{\partial(F_t - E_{t-1}F_t)} = \frac{1}{rr(\partial f / \partial ff_t)} < 0 .$$

In order to estimate the liquidity effect one must make an assumption about the demand for reserves. Following Hamilton (1997) assume that demand is linear, i.e.,

(14) $$f(ff_t, y_t) = -\beta ff_t + \alpha y_t + \eta_t ,$$

where α and β are positive fixed parameters and η_t denotes an $i.i.d.$ random disturbance with mean zero and a constant variance. With these assumptions, (12) can be rewritten as

(15) $$ff_t = -(1/rr\beta)^{-1}[-rr\tilde{\beta} ff_t^* + (F_t - E_{t-1}F_t) + (BR_t - IBA_t) - (rr\alpha y_t - rr\tilde{\alpha}\tilde{y}_t) - (ER_t - E_{t-1}ER_t^d) + k_t - \eta_t],$$

where ~ denotes the Desk's estimate of the corresponding parameter or variable.

2.2 The Role of Reserve Requirements

It is clear from equation (4) that the relationship between the daily and policy relevant liquidity effects also depends on the Fed's system of reserve requirements. There are several factors that are relevant in this regard. Important among these are exogenous and endogenous reductions in reserve requirements. The Fed made two major exogenous reductions in reserve requirements during the past two decades. The first occurred in December 1990; the second in April 1992.[11]

There was also an important endogenous change in effective reserve requirements. In 1994 banks began sweeping their retail transactions deposit accounts to

[11] Effective December 13, 1990, the 3 percent reserve requirement on non-transaction liabilities was reduced to 1.5 percent for weekly reporters; and effective December 27, 1990, the 1.5 percent reserve requirement on non-transaction liabilities was reduced to zero for weekly reporters. The combined effect of these actions reduced required reserves by an estimated $13.2 billion. While not reported here, these changes appear to have had no important effect on the estimates of the daily liquidity effect reported in Section 3. There have been numerous other changes in the Fed's in the percentage reserve requirements over the years; however, these were relatively small and of little consequence.

reduce their effective reserve requirement (e.g., Anderson and Rasche, 2001). The result was a significant reduction in effective reserve requirements and a significant rise in the number of nonbound banks, i.e., banks that satisfy their reserve requirements with vault cash.[12] This change has important consequences for the relationship between the daily and policy-relevant liquidity effects because it severs the contemporaneous link between money demand and reserve demand for banks that satisfy their reserve requirement with vault cash. This means that estimates of the daily liquidity effect that reflects the behavior of nonbound banks have no implication for the policy-relevant liquidity effect. This is extremely important because reserve demand may be interest sensitive for reasons other than the interest sensitivity of money demand.

Unfortunately, there is no way to identify reserves demanded by bound versus nonbound banks. However, in July 1998 the Fed reintroduced lagged reserve accounting. Beginning with the maintenance period that began on July 30, 1998, there is a full two-maintenance-period lag in the reserve accounting system, i.e., reserve requirements for the current maintenance period are determined by deposit balances held during the fourteen-day period two maintenance periods previous. The re-introduction of lagged reserve accounting severs the contemporaneous link between money demand and reserve demand for all banks, not simply nonbound banks. Hence, there is no contemporaneous relationship between the daily and policy-relevant liquidity effects after July 1998. Estimates of the daily liquidity after this date have no implications for Friedman's policy-relevant liquidity effect. Hence, contrary to their claim Carpenter and Demiralp's (2006) evidence of a daily liquidity effect after July 1998 has no implications for the policy-

[12] See Anderson and Rasche (2001) for more details on the effects of retail sweep programs.

relevant liquidity effect.

Reserve demand is interest sensitive even when there is no contemporaneous link between money demand and reserve demand because banks are required to hold reserves and, consequently, have an incentive to economize on their holdings of non-interest-bearing deposits with the Fed.

Thornton (2001a) has noted that there was a two-day lag in the Fed's prior reserve accounting system from March 1984 to July 1998.[13] Specifically, a bank's maintenance-period reserve requirement was based on deposit balances held two days prior to the end of the maintenance period. The lack of a contemporaneously relationship between money demand and reserve demand on those days means that evidence of a daily liquidity effect on the last two days of the maintenance period has no implication for the policy-relevent liquidity effect.

Analyses by Clouse and Dow (2002) and Bartolini, Bertola, and Prati (2002); however, show that reserve demand may be related to money demand on the last two days of the maintenance period if individual banks behave optimally with respect to the reserve carryover provision.[14] These models do not include the costs of operating such procedures. These costs may be large relative to the cost of satisfying a reserve shortfall at the end of the maintenance period through the discount window or some other means.[15] Consequently, it is not clear that such intense reserve management—though technically feasible—is economically viable.[16] In any event, even if banks behave

[13] From 1968 to March 1984 there was a one-maintenance-period lag in the Fed's system of reserve accounting.
[14] I would like to thank Jim Hamilton for pointing out this possibility to me.
[15] For example, the one-day cost of paying a 1-percentage-point premium on a $100 million dollar reserve shortfall is $2,739.73.
[16] There is also no direct evidence that banks actually implement such procedures. Indeed, anecdotal

optimally, the relationship between the daily and policy-relevant liquidity effects would be affected by the fact that reserve demand on these days would be affected by the carryover provision. Consequently, the extent to which estimates of the response of the funds rate to a reserve supply shock on the last two days of the maintenance period provide evidence of the policy-relevant liquidity effect is uncertain.

The relationship between the daily and policy-relevant liquidity effects also can be distorted on days when there are large idiosyncratic shocks to the funds rate. Thornton (2001a) has shown that such distortion can be large on settlement Wednesdays. Hence, special care is taken in estimating the daily liquidity effect on those days.

The dependent variable in equation (15) is ff_t and not $ff_t - ff_t^*$, as in Carpenter and Demiralp (2006) or Δff_t as in Hamilton's (1997). It is clear from equation (15) that $ff_t - ff_t^*$ is the appropriate dependent variable if and only if the Desk correctly estimates the interest elasticity of money demand, i.e., $\tilde{\beta} = \beta$.

Hamilton (1997) and Carpenter and Demiralp (2006) note that a necessary condition for obtaining unbiased estimates of the daily liquidity effect is that reserve supply shocks be uncorrelated with shocks to money demand, η_t. However, equation (15) shows that $F_t - E_{t-1}F_t$ must also be uncorrelated with $BR_t - IBA_t$, k_t, $ER_t^d - E_{t-1}ER_t^d$, and $rr\alpha y_t - rr\tilde{\alpha}\tilde{y}_t$ —variables not included Hamilton's (1997) or Carpenter and Demiralp's (2006) models.

3. Estimates of the Daily Liquidity Effect

This section estimates the daily liquidity effect based on the model developed in

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evidence from reserve account managers of two very large New York banks in the late 1990s suggests that these banks did not rely on such procedures to manage their reserves.

Section 2. The analysis employs an EGARCH (1, 1) model. Following Hamilton (1997) and Carpenter and Demiralp (2006) the daily liquidity effect is estimated using an EGARCH model. The EGARCH model is in the class of autoregressive conditional heteroskedastic (ARCH) models developed by Engle (1982), and was introduced by Nelson (1991). The specification takes the general form

(17) $$ff_t = X_t\beta + \varepsilon_t, \quad t = 1, 2, ..., T$$

where X_t denotes a 1-by-l vector of l regressors and β denotes the corresponding l-by-1 vector of coefficients. The variance of ε_t, σ_t^2, is assumed to be conditionally heteroskedastic. Specifically,

(18) $$\log \sigma_t^2 = \xi + \gamma \left| \frac{\varepsilon_{t-1}}{\sigma_{t-1}} \right| + \psi \frac{\varepsilon_{t-1}}{\sigma_{t-1}} + \varsigma \log \sigma_{t-1}^2 + Z_t\delta + \omega_t,$$

where Z_t is a 1-by-m vector of observable variables that determine the evolution of the variance and δ is a corresponding m-by-1 vector of coefficients. The coefficient ψ allows for the possibility of asymmetry in the response of shocks to the funds rate. Because ARCH models account for heteroskedasticity, they produce estimates of β that are generally more efficient than ordinary least squares.

Figure 1 presents ff_t and ff_t^* over the period January 2, 1986, through January 20, 2004. There are a number of volatility clusters typical of ARCH. Some of these are associated with well-defined events, such as the marked increases in volatility associated with the 1987 stock market crash (bracketed by the first two vertical lines) and the surprise reduction in reserve requirements in 1990 (bracketed by the third and fourth vertical lines). There is also a marked decline in volatility that appears to begin in early 2000 (denoted by the fifth vertical line), which may be associated with changes in the

FOMC's disclosure procedures. Moreover, there are a relatively large number of volatility spikes—days when the funds rate changed by a relatively large amount only to return to essentially its previous day's level the next day. These spikes are often unique to the funds rate. Some are associated with well-known events (e.g., settlement Wednesday, and the first and last days of the year, or quarter); others are not. To account for spikes in the funds rate associated with well-known events, following Hamilton and Carpenter and Demiralp, dummy variables are used for each of the 10 maintenance period days (Di, $i = 1,2,...,10$); for the first and last days of the month, quarter, and year ($bom, eom, boq, eoq, boy, eoy$); for the 15th day of the month (mom); for the day before and after holidays; for the day before and after changes in the funds rate target ($bh, ah, btar, atar$); for the month of December (dec); and for the first and second week of the maintenance period ($w1, w2$).[17] Dummy variables are also included for the period of the 1987 stock market crash ($d1987$) and the surprise change in reserve requirements ($d1990$).[18] The error the staff of the Board of Governors makes each day in forecasting F_t is the reserve supply shock and is denoted $miss$.[19] Separate estimates of the demands for required and excess reserves are made by the staffs of the Federal Reserve Bank of New York and the Board of Governors; however, Board's estimates are used here.

Because of the introduction of sweep accounting in January 1994, initially the

[17] If the 15th falls on a weekend or a holiday, mom takes on the value of 1 on the business day closest to the middle of the month.

[18] $d1987$ takes on the value 1 from the first day of the stock market crash, October 19, 1987, through December 31, 1987, and zero elsewhere. $d1990$ takes on the value 1 from the first settlement Wednesday affected by the changes, December 13, 1990, through February 28, 1991, and zero elsewhere.

[19] The Board Staff's estimate is a proxy because in reality, the staffs of the Board and the New York Fed make independent estimates of the autonomous factors. The Treasury makes an independent estimate of one of the factors, namely, its balance at the Fed. Exactly how these estimates are combined each day in conducting open market operations is unclear. See Thornton (2004) for further details.

model is estimated over sample period January 2, 1986 though December 31, 1993. Carpenter and Demiralp found the daily liquidity effect to be nonlinear, being statistically significant for large shocks (shocks larger than $1 billion) but not for small shocks (shocks $\leq$ $1 billion). Hence, $miss$ is partitioned into large shocks ($miss_t^{lg}$) and small shocks ($miss_t^{sm}$) using their criterion. Because of the two-day lag in the Fed's system of reserve requirements during this period, settlement days are partitioned into the last two days of the maintenance period ($l2d$) and all other days ($nl2d$).[20] Also, because the effect of reserve supply shocks on the funds rate will be different on days when the funds rate target is changed, dummy variables for days when the target was changed ($d\Delta ff_t^*$) and other days ($dn\Delta ff_t^*$) are included. Finally, the Student's t distribution is used rather that the normal distribution to account for the thick tails in the distribution of the funds rate.

The results are presented in Panels A, B, and C for Specification 1 of Table 1. The first column of each specification reports the parameter estimate, and the second column reports the corresponding significance level of the test that the coefficient is zero. Panel A reports the estimates of β for the parameters that are particularly relevant for evaluating the daily and policy-relevant liquidity effects. Panel B reports the estimates for the remaining parameters of β. Panel C reports the estimates of the variance parameters and the relevant summary statistics.

The estimates of the variance parameters in Panel C for Specification 1 show that

[20] Hamilton and Demrialp partition $miss$ by each day of the maintenance period. However, save the last two days of the maintenance period, there is no particular reason to believe that the slope of the money demand curve should be systemmaticlly different on different days of the maintenance period. Consequently, this is not done here.

the variance increased significantly during the periods immediately following the 1987 stock market crash and following the 1990 surprise reduction in reserve requirements. Also, the estimate of degrees of freedom (dof) is very small, 3.77, and highly statistically significant, indicating the appropriateness of using the Student's t distribution.

Panel B reports estimates of the "nuisance" parameters designed to account for certain day-specific effects. All but a few of these estimates are statistically significant. In most cases the estimated responses are as one might expect, e.g., the funds rate tends to be higher on settlement Wednesdays, higher at the end of the quarter, the first and last days of the month, etc.

Panel A reports the estimates relevant for the daily and policy-relevant liquidity effects. As expected, reserve supply shocks that occur on days when the FOMC changed the funds rate target are not statistically significant, regardless of whether the shocks are large or small. Also, consistent with Carpenter and Demiralp (2006), the response of the funds rate to small shocks on all but the last two days of the maintenance period is statistically significant and smaller than the response to large shocks. However, the magnitude of the difference between the response to large and small shocks is relatively small. Indeed, the likelihood ratio test statistic for equality of the response is 0.464 , which is not statistically significant. Hence, there is no evidence of nonlinearity.

There is a statistically significant difference in the response of the funds rate on the last two days of the maintenance period relative to other days. Indeed, the response is considerably larger, about three times as large.

The coefficients on $BR_t - IBA_t$, k_t , and err_t^D are all statistically significant at very

low significance levels. The coefficient on $BR_t - IBA_t$ is positive, suggesting that borrowing above the FOMC's assumed level is associated with the funds rate above the target. The sign of the coefficient is inconsistent with a supply shock interpretation, but is consistent with the evidence that borrowing responds endogenously to the funds rate (e.g., Thornton, 2001b). The coefficients on k_t and err_t^D have the anticipated signs. The estimated coefficient on k_t suggests that the funds rate tends to be significantly lower on days when the Desk engages in more open market operations than the operating procedure suggests. Likewise, if the Desk underestimates the demand for reserves, the funds rate is somewhat higher. Note that a positive value of err_t^D is conceptually the same as a negative reserve supply shock. Consistent with theory, the estimated coefficients on err_t^D and $miss$ on other than the last two days of the maintenance period are similar in magnitude but opposite in sign. Indeed, the likelihood ratio statistic for the hypothesis that the responses are equal but opposite in sign is 0.79.

Given the lack of statistically significant nonlinearity in the response to shocks, the model is re-estimated assuming that there is no difference in the response of the funds rate to large or small shocks. These results are reported in Specification 2 of Table 1. The estimated coefficients are nearly identical to those reported for Specification 1. Importantly, the response on the last two days of the maintenance period is three times larger than on other days.

To investigate the sensitivity of the estimates to unusually large, idiosyncratic shocks to the funds rate, the observations are partitioned into days when there are large idiosyncratic shocks to the funds rate, i.e., outliers (*O*), and days when there are no outliers (*NO*). Shocks to the funds rate are estimated by regressing the federal funds rate

on a constant and the 3-month Treasury bill rate over the period. The residuals from this equation represent idiosyncratic movements in the federal funds rate. As such, the response of the funds rate on such days provides no information about a policy-relevant liquidity effect. Outliers are days when the shocks to the funds rate are more than 80 basis points (roughly two standard errors).[21] There were 62 such days during this sample period (slightly more than 3 percent of the days), 33 of which occurred on a settlement Tuesday or Wednesday.

Estimates with the variables partitioned by outliers are reported in Specification 3 of Table 1. As anticipated, estimates of the daily liquidity effect are sensitive to idiosyncratic shocks to the funds rate. On days when there are large idiosyncratic shocks to the funds rate, the estimated daily liquidity effect is many times larger than on days when there are no outliers. Consistent with the results of Thornton (2001a) estimates of the daily liquidity effect on Settlement Wednesdays and other days when there are large shocks to the funds rate overestimates the magnitude of both the daily and policy-relevant liquidity effects. The estimate of the daily liquidity effect that is most indicative of the policy-relevant liquidity effect is the estimate on other than the last two days of the maintenance period when there are no large idiosyncratic shocks to the funds rate.[22] That this is the case is supported by the fact that this estimate is nearly equal but opposite in

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[21] As a robustness check on the qualitative results values of 40, 50, and 60 basis points were also used. The qualitative conclusion about the coefficient $miss$ on NO days is invariant to the value used.

[22] Given the close relationship between the funds rate and the funds rate target, the model was also estimated using $ff_t - ff_t^*$ as the dependent variable. While the coefficient estimates changed somewhat, the qualitative conclusions are not sensitive to whether ff_t or $ff_t - ff_t^*$ is the dependent variable. The quantitative and qualitative results are very sensitive to excluding $BR_t - IBA_t$, err_t^D, and k_t, however. The correlations between $miss$ and $BR_t - IBA_t$, err_t^D, and k_t over this sample period are -0.058, 0.352, and -0.013, respectively.

sign to the coefficient on reserve demand forecast errors. Again, the null hypothesis that these coefficients are equal and opposite in sign is not rejected. The likelihood ratio statistic is 1.066.

3.1 Post-1993 Estimates of the Daily Liquidity Effect

The introduction of sweep accounts in January 1994 dramatically reduced reserve requirements for banks over time. Anderson and Rasche (2001) show that sweep activity significantly reduced deposit liabilities that were subject to reserve requirements by the end of our sample period, December 31, 1996. They conclude that by the end of 1999 "the willingness of bank regulators to permit use of deposit-sweeping software has made statutory reserve requirements a 'voluntary constraint' for most banks." To investigate the effect of sweep accounts on the estimate of the daily liquidity effect, the model is estimated over the period January 3, 1994, through December 31, 1996. To conserve space, only estimates of the parameters that are relevant for the liquidity effect are reported in Table 2. All of the estimated coefficients on the various partitions of $miss$ are much smaller in absolute value than those reported in Table 1. Moreover, none is statistically significant at the 5 percent significance level. The estimate is statistically significant at slightly higher than the 5 percent significance level when $miss$ is partitioned by $nl2d$ and NO. The estimate is only about half as large as that for the pre-1994 period, which is inconsistent with expectations given that sweeps effectively reduce reserve requirements—all other things the same, lower effective reserve requirements should have resulted in a larger coefficient estimate. One possible explanation is that the effective elimination of mandatory reserve requirements for non-bound banks significantly altered the interest sensitivity of aggregate reserve demand independent of

money demand. In any event, consistent with theory, the estimated coefficient on *miss* for these days is equal but opposite in sign to that of reserve demand shocks.

Finally, the model was estimated over the period August 3, 1998, through January 30, 2004. It is important to note that $BR_t - IBA_t$, err_t^D, and k_t are not available over this period, so the estimates are likely to be biased. More importantly, because the introduction of lagged reserve accounting effectively severed the contemporaneous relationship between money and reserve demand, estimates of the daily liquidity effect have no implication for the policy-relevant liquidity effect. The estimate for other than the last two days of the maintenance period when there were no outliers is -0.007 and statistically significant at a very low significance level. This estimate shows that the demand for reserves can be interest sensitive apart from the interest sensitivity of money demand.

4. Conclusions

The daily liquidity effect was first investigated by Hamilton (1997) in an attempt to find evidence of Friedman's (1969) policy-relevant liquidity effect that had escaped detection using lower frequency, monthly and quarterly, data. The daily liquidity effect is directly linked to the policy-relevant liquidity effect by Federal-Reserve-imposed reserve requirements. This paper analyzed the relationship between the policy-relevant and daily liquidity effects using a comprehensive model of the Desk's operating procedure. The analysis shows that the relationship between the daily and policy-relevant liquidity effects depends on the Desk's operating procedure, the Fed's system of reserve requirements, and other factors. Importantly, the analysis shows that there is no relationship between these liquidity effects after July 1998 when the Fed reinstated

lagged reserve accounting.

Estimates of the model using data before 1994 suggest that there may have been a statistically significant policy-relevant liquidity effect prior to 1994. The estimated daily liquidity effect is small, however. For example, according to this estimate it would take roughly a $10 billion reserve supply shock to generate about a 20-basis-point change in the funds rate. If one assumes that the average effective reserve requirement during this period is 10 percent, this would be equivalent to about a $100 billion shock to the money supply. Because banks have an incentive to economize on their holdings of reserves, reserve demand is interest sensitive after the Fed reinstated lagged reserve accounting in July 1998. Estimates of a statistically significant daily liquidity effect after July 1998, reported here and elsewhere, however, have no implications for the policy-relevant liquidity effect. They merely confirm the interest sensitivity of reserve demand.

The analysis presented here suggests that it is no easier to find convincing proof of a statistically significant and economically important policy-relevant liquidity effect using high-frequency daily data than it has been using lower frequency (monthly and quarterly) data. A resolution of the liquidity puzzle remains elusive.

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Table 1: Estimates of the Reserve Market Model: January 2, 1986 – December 31, 1993

Panel A						
Variable	Specification 1		Specification 2		Specification 3	
ff_t^*	0.5555	0.0000	0.5523	0.0000	0.5580	0.0000
Δff_t^*	0.0003	0.3820	0.0004	0.3238	0.0004	0.3320
$miss_t^{sm} \text{ x } d\Delta ff_t^*$	0.0104	0.5593	0.0109	0.1679	0.0106	0.1763
$miss_t^{sm} \text{ x } dn\Delta ff_t^* \text{ x } l2d$	-0.0047	0.8203				
$miss_t^{sm} \text{ x } dn\Delta ff_t^* \text{ x } nl2d$	-0.0083	0.0219				
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } l2d$			-0.0327	0.0000		
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } nl2d$			-0.0109	0.0000		
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } l2d \text{ x } O$					-0.2181	0.0000
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } l2d \text{ x } NO$					-0.0275	0.0001
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } nl2d \text{ x } O$					-0.1195	0.0049
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } nl2d \text{ x } NO$					-0.0108	0.0000
$miss_t^{lg} \text{ x } d\Delta ff_t^*$	0.0113	0.1887				
$miss_t^{lg} \text{ x } dn\Delta ff_t^* \text{ x } l2d$	-0.0323	0.0000				
$miss_t^{lg} \text{ x } dn\Delta ff_t^* \text{ x } nl2d$	-0.0114	0.0000				
$BR_t - IBA_t$	0.0243	0.0000	0.0239	0.0000	0.0239	0.0000
err_t^D	0.0088	0.0000	0.0089	0.0000	0.0088	0.0000
k_t	-0.0048	0.0003	-0.0046	0.0005	-0.0047	0.0004

Table 1 Continued

	Panel B					
Variable	Specification 1		Specification 2		Specification 3	
ff_{t-1} x $w1$	0.4472	0.0000	0.4504	0.0000	0.4447	0.0000
ff_{t-1} x $w2$	0.4461	0.0000	0.4494	0.0000	0.4436	0.0000
$D1$	-0.0132	0.2335	-0.0126	0.2555	-0.0130	0.2425
$D2$	-0.0556	0.0000	-0.0691	0.0000	-0.0683	0.0000
$D3$	0.0468	0.0000	0.0340	0.0001	0.0342	0.0001
$D4$	-0.0287	0.0015	-0.0414	0.0000	-0.0413	0.0000
$D5$	-0.0351	0.0001	-0.0482	0.0000	-0.0482	0.0000
$D6$	0.0053	0.6869	-0.0085	0.2980	-0.0077	0.3445
$D7$	-0.0514	0.0001	-0.0649	0.0000	-0.0640	0.0000
$D8$	0.0542	0.0006	0.0398	0.0006	0.0403	0.0004
$D9$	-0.0399	0.0224	-0.0537	0.0001	-0.0524	0.0002
$D10$	0.0817	0.0000	0.0678	0.0000	0.0690	0.0000
eom	0.0871	0.0000	0.0861	0.0000	0.0881	0.0000
bom	0.0572	0.0000	0.0573	0.0000	0.0570	0.0000
eoq	0.2125	0.0032	0.2159	0.0028	0.2000	0.0035
boq	-0.1152	0.0070	-0.1176	0.0056	-0.1202	0.0035
eoy	-0.3804	0.0003	-0.3810	0.0003	-0.3675	0.0004
boy	0.4270	0.0006	0.4301	0.0005	0.4351	0.0005
mom	0.0899	0.0000	0.0904	0.0000	0.0903	0.0000
bh	-0.0169	0.0329	-0.0163	0.0398	-0.0173	0.0297
ah	0.1097	0.0000	0.1094	0.0000	0.1095	0.0000

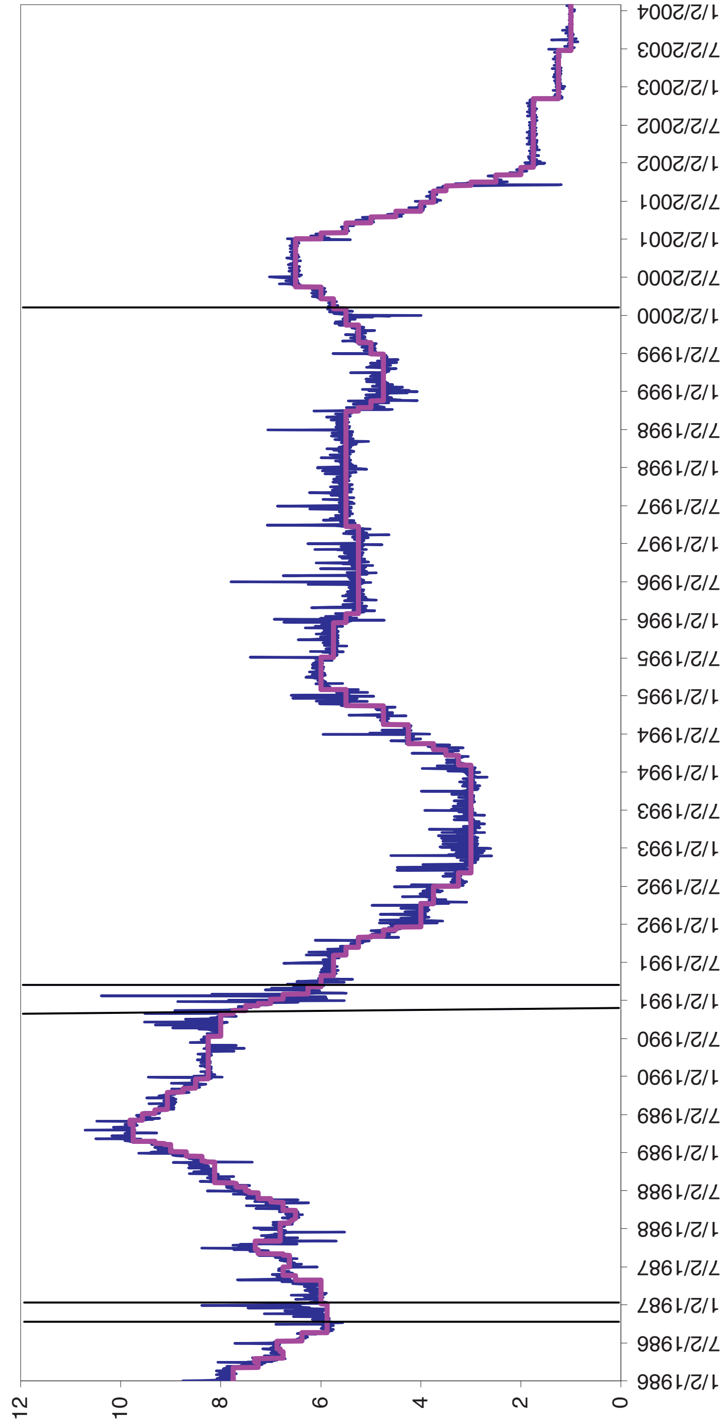
Table 1 Continued

Panel C						
Variables	Specification 1		Specification 2		Specification 3	
const.	-3.0817	0.0000	-3.0848	0.0000	-3.0208	0.0000
$\lvert \frac{\varepsilon_{t-1}}{\sigma_{t-1}} \rvert$	0.7053	0.0000	0.7043	0.0000	0.6821	0.0000
$\frac{\varepsilon_{t-1}}{\sigma_{t-1}}$	0.0559	0.2237	0.0585	0.2058	0.0638	0.1507
$\log \sigma^2_{t-1}$	0.5387	0.0000	0.5374	0.0000	0.5466	0.0000
$D1 + D2 + D3$	1.5364	0.0000	1.5356	0.0000	1.5135	0.0000
btar	0.6902	0.0085	0.6768	0.0086	0.6660	0.0097
ah	1.1983	0.0000	1.2091	0.0000	1.1562	0.0000
eom	0.9886	0.0000	-1.8576	0.0096	-1.6951	0.0161
eoq	2.4000	0.0000	2.4184	0.0000	2.3238	0.0000
eoy	-1.8168	0.0108	0.9883	0.0000	0.9508	0.0000
mom	0.6470	0.0028	0.6558	0.0024	0.6322	0.0033
*d*1987	0.4993	0.0239	0.4942	0.0251	1.3252	0.0000
*d*1990	1.3196	0.0000	1.3238	0.0000	0.5740	0.0099
dof	3.7653	0.0000	3.7529	0.0000	3.7440	0.0000
No. of Obs.	1966		1966		1966	
$\bar{R}^2$	0.9887		0.9885		0.9892	
s.e.	0.2234		0.2244		0.2180	
Log Likelihood	1477.061		1475.596		1479.130	

Table 2: Estimates of the Reserve Market Model: January 3, 1994 - December 31, 1996.

Variable	Coefficient	Significance Level
ff_t^*	0.769	0.000
Δff_t^*	-0.000	0.820
$miss_t^{sm} \text{ x } d\Delta ff_t^*$	0.769	0.000
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } l2d \text{ x } O$	0.000	0.820
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } l2d \text{ x } NO$	-0.008	0.881
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } nl2d \text{ x } O$	-0.011	0.281
$miss_t \text{ x } dn\Delta ff_t^* \text{ x } nl2d \text{ x } NO$	-0.004	0.051
$BR_t - IBA_t$	0.198	0.000
err_t^D	0.004	0.006
k_t	0.000	0.770
$No.\ of\ Obs.$	754	
$\bar{R}^2$	0.946	
s.e.	0.197	
Log Likelihood	789.248	

Figure 1 Effective Federal Funds Rate and the FOMC's Funds Rate Target
(January 2, 1986 - January 20, 2004)



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