

Lee, Yungsook

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The Federal Funds Market and the Overnight Eurodollar Market

Yungsook Lee*

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Abstract

Overnight Federal funds and overnight Eurodollars are among the most liquid short-term assets that a bank can hold to acquire required reserves. They are traded overnight and denominated in U.S. dollars. They also have different characteristics: The Fed funds market and the Eurodollar market are located in different places, and the transaction volume is larger in the overnight Eurodollar market than in the Fed funds market. This paper is an empirical work on the relationship between the Federal funds rate and the overnight Eurodollar rate. Hamilton (1996) found that the Fed funds rate exhibited calendar day effects over 1984-1990. I find that the overnight Eurodollar rate exhibits very similar calendar day effects but the absolute magnitudes are slightly less in general over 1984-1997. The empirical results support the hypothesis that the tendency in daily changes in the Federal funds rate and in the overnight Eurodollar rate are caused by line limits, transaction costs and accounting convention in the Federal funds market. The differential between the Fed funds rate and the overnight Eurodollar rate is predictable and it possibly provides the evidence against the efficient market hypothesis.

JEL: C5; E4; E5

Keywords: Interest Rate Differential, Transaction Costs, Efficient Market Hypothesis, Calendar Effects

Yungsook Lee, Department of Economics, University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0508
Email: yslee@weber.ucsd.edu

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I. Introduction

When a bank is short of reserves, it has several options. It can purchase Federal funds, borrow Eurodollars, sell securities under repurchase agreements (RPs), sell large certificates of deposit (CDs) or borrow from the Fed through the discount window. Because of the limitations on frequent borrowing at a discount window, however, the individual bank will explore other ways to adjust its reserve position before it turns to the discount window. Hamilton (1998) found that a shock to nonborrowed reserves had no effect on discount window borrowing unless it occurred on the last day of a maintenance period or the last day of the quarter. A bank has to tap other sources to get desired reserves. When a bank holds more excess reserves than desired, it wants to invest them into liquid assets rather than longer-term, less liquid assets. The bank does this in order to cover the unexpected withdrawal of deposits or to make unexpected loans. The bank dislikes holding excess reserves because reserves, in the form of vault cash or deposits at the Federal Reserve, earn no interest but liquid assets do earn interest. A bank can sell Federal funds, buy Eurodollar deposits and CDs at other banks, buy securities through a reverse repurchase agreement, and so on. These assets are considered adjustment options to cover contingencies but they offer different levels of liquidity. Overnight Federal funds, overnight Eurodollars and overnight RPs are the most liquid among short-term assets banks hold. Because these three assets are traded on an overnight basis and they are U.S. dollar denominated, arbitrage might keep interest rates on these assets closely aligned.

Eurodollars are U.S. dollar-denominated deposit liabilities of the Eurodollar market, which is an international telephone and telex network located in many countries outside the United States. The Eurodollar market is a wholesale market and most transactions involve amounts of \$41 million or more. The practice of accepting U.S. dollar-denominated deposits outside of the U.S. began in Europe and it has spread to Canada, several Caribbean islands, Hong Kong, Tokyo, Singapore, the International Banking Facilities (IBFs) in the United States and other financial centers. The largest center for Eurodollar activity is in London. The various branches of a bank located in London, Paris and elsewhere usually offer the same

interest rates on Eurodollars. A U.S. bank would not find it worthwhile to pay a higher interest rate on a London dollar deposit than on a Paris dollar deposit if the funds are to be used to finance a purchase of a loan in New York (Aliber, 1980). Occasionally, however, the branch in a particular country may offer a somewhat higher interest rate to compensate for depositor reluctance to buy deposits in that country because of greater political risk. Commercial and central banks, large corporations and governments are the major customers in Eurodollar banks. However, banks that participate in the Eurodollar market actively borrow and lend Eurodollars among themselves and interbank transactions alone have made up over 60 percent of the total volume over the 1980s and 1990s.

The Federal funds market is the interbank market for overnight lending of funds on deposit in a bank's reserve account at the Fed. It has been primarily made up of domestic commercial banks, thrift institutions, agencies and branches of foreign banks in the United States, Federal agencies, and government securities dealers. The competitively determined interest rate on loans in this market is called the Federal funds rate. Most large transactions of the Federal funds occur in the brokers' market. At the end of 1980s, trades through the brokers were typically for \$25 million or more but trades of around \$10 million were arranged routinely. Trades of about \$1 million were occasionally arranged (Meulendyke, 1989). The small financial institutions rarely generate excess reserves large enough to enable them to participate in the brokers' market. They usually find a correspondent bank directly and trade either at the opening rate or at the average effective Fed funds rate set in the brokers' market less a fraction.

There are over 10,000 commercial banks in the United States but only the 20 to 30 largest United States banks are particularly active in the Eurodollar market. For a big U.S. bank with a reserve deficiency, borrowing overnight Eurodollars is an alternative to purchasing Fed funds. Also, for a big-sized domestic bank with excess reserves, overnight Eurodollar deposits are an alternative to Fed funds sold. Eurodollars are close substitutes for Fed funds to such banks. However, for middle or small-sized banks, they are not close

substitutes. Because of this market friction, the overnight Eurodollar rate and the Fed funds rate might move differently.

Previous research studied the Granger-causality between the Eurodollar rate and U.S. domestic interest rate on compatible assets. Reinghart and Harmon (1987) examined the relationship between the daily Fed funds rate and the daily overnight Eurodollar rate. They studied the effect of the switch from next-day settlement to same-day settlement for Eurodollar deposits in October 1981. Their analysis relied on summary statistics and OLS estimation. They showed that this change caused a structural shift in the causal relationship between two markets. They argued that the Fed funds rate was not Granger-caused by the overnight Eurodollar rate but the overnight Eurodollar rate was Granger-caused by the Fed funds rate during the next-day settlement period. The overnight Eurodollar rate and the Fed funds rate Granger-caused each other during the same-day settlement period. Other early studies (Herdershott, 1967; Kwack, 1971; and Levin 1974) showed that US interest rates were not Granger-caused by Eurodollar rates and Eurodollar rates were Granger-caused by U.S. domestic interest rates. However, recent studies (Fung and Isberg, 1992; Fung and Lo, 1995) provided results that Eurodollar rates and U.S. domestic interest rates Granger-caused each other after the middle of 1980s, but with weaker feedback from Eurodollar rates to U.S. domestic interest rates. All of them interpreted the results as whether interest rate innovations originated primarily in the U.S. market or in the Eurodollar market. However, because the two interest rates were measured at different times within the same day, it might not be right to explain the results as Granger-Causality.

Hamilton (1996) found that the Fed funds rate had the following tendency over 1984-1990: The Fed funds rate fell during the reserve maintenance period until the second Friday. It decreased on Fridays and before U.S. holidays. It increased on Mondays and upsurged on settlement Wednesdays and after holidays. He explained that these features are the result of line limits, transaction costs and weekend accounting conventions in the Federal funds market. I analyze the relation between the Fed funds rate and the overnight rate between March 1984 and March 1997, focusing on whether the overnight Eurodollar rate showed the

same calendar effect as the Federal funds rate. This study considers outliers and GARCH effects in contrast to previous research. I reproduce the basic findings about the Fed funds rate as documented by Hamilton (1996) on a previous data set. The overnight Eurodollar rate exhibits very similar calendar effects but the absolute magnitudes are slightly less. These results support the hypothesis that the calendar day effects of the Federal funds rate and the overnight Eurodollar rate were caused by transaction costs in the Federal funds market. The differential between the Fed funds rate and the overnight Eurodollar rate is predictable, which can be interpreted in two different ways. First of all, it indicates that U.S. banks can get profit on an average by arbitrage between two markets. On the contrary, a second interpretation is that it does not mean profitability. Because the overnight London Interbank Offer Rate (LIBOR) at 11:00 a.m. Greenwich Mean Time (GMT) is used for the overnight Eurodollar rate and the overnight LIBOR is a reference rate, banks have to pay some margin over it and the overnight Eurodollar rate changes over time.

The paper proceeds as follows. Section 2 briefly describes reserve requirements, the Fed funds market, and Hamilton's (1996) research on the Federal funds rate. Section 3 describes the data and section 4 develops empirical models. The empirical results are reported in section 5. Section 6 evaluates the forecasting performance between my models and other alternative models. Section 7 concludes my paper and suggests further research.

II.Required Reserves and Federal Funds Market

Reserves are the sum of vault cash and end-of-day reserve balances directly with the Federal Reserve Bank in the Federal Reserve District in which it is located. A depository institution, a U.S. branch or agency of a foreign bank, and an Edge or agreement corporation must maintain required reserves, which are computed as various fractions of end-of-day deposits under Federal Reserve Board regulations. To satisfy the reserve requirements, the average daily level of reserves during the two-week maintenance period must equal or exceed the required reserves during the two-week computation period. Otherwise, banks are subject to financial penalties. Figures 1.A, 1.B and 1.C indicate the reserve accounting system 1984

though 1997. Since 1984, the maintenance period over which reserves must be held is a two-week period beginning on a Thursday and ending on a Wednesday. The last Wednesday of the maintenance period is called settlement Wednesday. The computation period is a two-week period for computing the average required reserves on the basis of daily average balances of deposits. Reserves required against transaction deposits are computed against the average end-of-day transaction deposits at the bank during the computation period. The computation period against transaction deposits began on a Tuesday and ended on a Monday two days before the end of the reserve maintenance period. The computation period was amended in July 1998 and since then it ends three days before the beginning of the maintenance period. For required reserves against nontransaction deposits, the computation period was also a two-week period ending two weeks prior to the beginning of the reserve computation period for transaction deposits. To calculate a bank's average reserves, the Fed added the average of a bank's deposit at the Federal Reserve during the reserve maintenance period and the average of daily vault cash during a two-week period which had ended on Monday two-weeks before the computation period for transaction deposits. In 1992, the Federal Reserve shortened by two weeks the lag in counting vault cash toward required reserves. Banks receive credit in a maintenance period for excess reserves they held in the previous period. Any deficiency in a maintenance period can also be made up by excess reserves in the following period. The maximum amount of any such excess or deficiency that is carried over was 2 percent of required reserves or \$25,000, whichever was greater. Since 1992, the carryover allowance has doubled to the larger of 4 percent of required reserves or \$50,000. The total transaction deposits are calculated by adding transaction deposits for each calendar day over the computation period. The transaction deposits on Friday are multiplied by three or, if the next Monday is a one-day holiday, four, as directed by the weekend accounting conventions. A bank did not know the amount of reserve requirements until the second Tuesday of the two-week period and did not know the amount of reserve balances at the Fed until the end of a maintenance period, so the bank needed to estimate both amounts within the maintenance period. A bank can vary the amount of its reserves to meet the

reserve requirements on the settlement Wednesday and therefore, the settlement Wednesday is very important to all banks.

Nonpersonal time deposits had been subject to the 3 percent reserve requirement prior to 1990. The 3 percent reserve requirement on nonpersonal time deposits was eliminated in 1990. The Federal Reserve established a 3 percent reserve requirement on the first \$30-\$50 million of transaction deposits during 1984-1997. All transaction deposits in excess of that amount had been subject to a 12 percent reserve ratio. In 1992, required reserves were cut from 12 percent to 10 percent. U.S. banks had been required to keep 3 percent reserves on Eurodollar borrowing in excess of their funds abroad. It was changed to 0 percent in 1990.

The Federal funds market is the market for immediately available reserve balances at the Federal Reserve. Federal funds are reserve balances held at Federal Reserve Banks. The Federal Reserve does not pay interest on reserve accounts, so banks have an incentive to minimize reserve balances and to lend reserves beyond their required reserves or desired excess reserves. The Fed funds rate is a barometer of the tightness of credit and a key monetary policy instrument. All other short term interest rates relate to the Fed funds rate.

Most Federal funds transactions are overnight loans between two depository institutions. The funds are lent out on one day and repaid with interest the next day. The Federal funds market acts as a means of distributing reserves throughout the banking system. Many relatively small institutions that generate reserves in excess of their requirement sell Federal funds at the Federal funds market. Many large banks borrow Federal funds to meet required reserves and to expand their sources of funds. Federal funds purchased have become an important source of funds for most large banks. Medium-sized and small-sized banks only occasionally purchase Federal funds.

Because Fed funds transactions usually are unsecured by anything other than verbal agreements, a bank limits the size of transaction for each buyer to minimize the seller's exposure to default risk. Banks with particularly poor credit risks might be unable to borrow Federal funds.

Since reserves held on any day of the two-week maintenance period are perfect substitutes for purpose of meeting reserve requirements, the Federal funds rate would follow a martingale within a two-week maintenance period under the following conditions: banks are risk neutral, the reserve requirement is the only reason why banks hold reserves, and there is no friction to participate in the Fed funds market (Hamilton, 1996). Under the martingale hypothesis, the Fed funds rate on day t is equal to the expected Fed funds rate on day $t + 1$. However since reserves on the first Thursday of a maintenance period are not substitutable for reserves of the day before, the Wednesday-Thursday change between two different maintenance periods may not be subject to the martingale hypothesis.

Hamilton (1996) tested the martingale hypothesis during the sample period from March 1, 1984 to November 28, 1990, considering day of a maintenance period, holidays, the end of a quarter and the end of a year. The estimated results showed that the Fed funds rate did not follow a martingale and banks did not consider reserves held on different days of the maintenance period as perfect substitutes. The rate fell during the reserve maintenance period until the second Friday. It sharply decreased on Fridays and jumped back up on Mondays. It fell before U.S. holidays and rose after holidays. It upsurged on settlement Wednesdays. He proposed the model, which explained these tendencies as the result of line limits, transaction costs and accounting conventions in the Federal funds market. He accounted for three main features in the Fed funds rate. First, the line limits caused the Fed funds rate to fall during the reserve maintenance period until the second Friday. A bank wanted to borrow early in the maintenance period due to line limits even if it knew the Fed funds rate would be cheaper later on in the maintenance period. Second, the Fed funds rate tended to drop on Friday and before holidays and increased Mondays and after holidays. The banks wanted to supply weekend funds, in order to 3 day's worth of interest. Furthermore, since a bank did not want unneeded excess reserves and it was not sure whether it needed the full reserve credit it could obtain from a multiple day loan, a bank preferred not to borrow a multiple day loan such as a two-day loan, a three-day loan or a four-day loan. A third characteristic is that the Fed funds rate tended to rise at the end of the maintenance period. Since a bank could perceive the exact

amount of needed reserves on settlement Wednesday due to the reserve accounting system, it delayed its borrowing until settlement Wednesday to avoid unneeded reserves.

However, because he analyzed the effective Federal funds rate, there might be two other possibilities from which the tendency might have come. The first possibility is it might reflect the fact that one day more trades took place at the bid side and next day more trades came at the asked side. Hence, the Federal funds rate could be higher on the second day and be fluctuating over the maintenance period even if the bid rate and the asked rate were constant over the period. The second possibility is that the tendency might result from a serial correlation in banks' behavior in that different types of banks borrowed Federal funds on different days. For example, riskier banks tended to borrow on Monday so there was a positive effect of Monday dummy variable on the Federal funds rate.

III. Description of Data

My data set consists of the daily Fed funds rate and the daily overnight Eurodollar rate, quoted as an annual rate. For the Fed funds rate, I use the effective Federal funds rate, a weighted average of the funds rates that prevailed during the day where the weights used are the amounts of funds that traded at each of the funds rates that prevailed. The overnight London Interbank Offer Rate (LIBOR) at 11:00 a.m. Greenwich Mean Time (GMT), which corresponds to 6:00 a.m. Eastern Standard Time (EST), is used for the daily overnight Eurodollar rate. LIBOR is the average of rates at which major international banks are willing to offer term Eurodollar deposits to each other. The LIBOR published by the British Bankers Association (BBA) is a benchmark rate in the Euromarket as well as other financial markets. The actual lending rate in Eurodollar markets is the London interbank rate plus some margin. London Interbank Bid Rate (LIBID), the rate at which major international banks are willing to take deposits from one another, is normally 1/8 percent below LIBOR. Even though there is no reason why market rates could not diverge from the 11 a.m. rate later in the day, the overnight London Interbank Offer Rate at 11:00 a.m. GMT is analyzed in this study because it is the only available Eurodollar rate in London.

My sample period is from March 1, 1984, which is the first day of a maintenance period, to March 26, 1997, which is the last day of a maintenance period. They amount to 3279 observations after excluding weekends, U.S. holidays and 7 trading days when the overnight Eurodollar rates are not available from the data set. Hamilton (1996) studied the Fed funds rate from March 1, 1984 to November 28, 1990; I extend the sample period. Because the one-week reserve maintenance period ending on Wednesday changed to a two-week reserve accounting system in February 1984, the period after March 1984 is covered in Hamilton (1996) and this study. Fed funds rates and overnight Eurodollar rates are plotted in Figure 2 and Figure 3 respectively. Figure 4 plots the differential between the Fed funds rate and the overnight Eurodollar rate. The Fed funds rate and the overnight Eurodollar rate show very similar movements and change very little on most days. Table 1 provides summary statistics of the Fed funds rate, the Eurodollar rate and their differential. The differential between the overnight Eurodollar rate and the Fed funds rate is very small with sample mean of -8 basis points. About 80 percent of the changes in daily Fed funds rates and differentials between the two rates occur within 25 basis points. About 90 percent of changes in overnight Eurodollar rates are within 25 basis points. However, changes in Fed funds rates and changes in overnight Eurodollar rates have the biggest outliers at the same calendar time, the ends of 1985 and 1986 when the last day of the year fell on the settlement Wednesday. The Fed funds rate and the overnight Eurodollar rate changed about 800 basis points and 1700 basis points at the end of 1986 respectively. The next biggest change in the Fed funds rate and the overnight Eurodollar rate was observed at the end of 1985, 438 basis points and 425 basis points respectively. The biggest outlier among differences between the overnight Eurodollar rate and the Fed funds rate was 106.5 basis points on Dec. 31, 1986. The standard deviations of the Fed funds rate and the overnight Eurodollar rate are almost equal and the standard deviation of the change in the Fed funds rate is smaller than that of the change in the overnight Eurodollar rate as seen in Table 1. However, by leaving out three observations (December 31, 1985 and December 30 and 31, 1986), the standard deviation of the Fed funds rate becomes larger than that of the overnight Eurodollar rate and the standard deviation of

the change in the Fed funds rate becomes much higher than that of the change in the overnight Eurodollar rate as Table 2 shows. Bigger outliers of the overnight Eurodollar rate make the standard deviation of the overnight Eurodollar rate the same as that of the Fed funds rate. The large kurtosis of the changes in Fed funds rates, changes in overnight Eurodollar rates and the differential between two interest rates indicates fat-tail distributions, requiring the analysis to consider large outliers.

IV. Model specification

Overnight Eurodollars and Fed funds are both traded for one business day and are both U.S. dollar-denominated. Since the amount of transactions in the Fed funds market and in the Eurodollar market is very large, the transaction cost is negligible for a bank that can participate in both markets. Hence the difference between the overnight Eurodollar rate and the Fed funds rate is defined as the excess return. A predictable excess return might reflect the limited substitutability and friction between two markets. These three variables are related by the following identity:

$$(4.1) \quad r_t = i_t + er_t,$$

where r_t is the overnight Eurodollar rate, i_t is the Fed funds rate and er_t is the excess return on the overnight Eurodollar rate over the Fed funds rate on day t . Here er_t is the differential between two overnight interest rates, which is defined as $er_t = r_t - i_t$. The conditional expected values are

$$(4.2) \quad E(r_t | I_{t-1}) = E(i_t | I_{t-1}) + E(er_t | I_{t-1}),$$

where $E(\cdot | I_{t-1})$ is the conditional expectation operator with respect to information set I_{t-1} , which is observed at date $t - 1$ in this bivariate model

$$(4.3) \quad I_{t-1} = \{i_{t-1}, i_{t-2}, \dots, r_{t-1}, r_{t-2}, \dots, t\}.$$

I adapt Hamilton's (1996) theoretical model for the Fed funds rate and add lagged overnight Eurodollar rates as explanatory variables. He noted that the martingale hypothesis might not restrict the Wednesday-Thursday change across different maintenance periods. The

Fed funds rate was also allowed to be variable and to depart from the martingale hypothesis on the last day of a quarter because of limited substitutability with reserves held on the day before or after. Hence if day t is the first day of a maintenance period or the first day of a quarter, the conditional mean for the Fed funds rate is specified as follows:

$$(4.4) \quad E(i_t | I_{t-1}) = \alpha_1 i_{t-1} + \alpha_2 i_{t-2} + \cdots + \alpha_p i_{t-p} + \delta_1 r_{t-1} + \delta_2 r_{t-2} + \cdots + \delta_q r_{t-q} + \eta_1 + \sum_{j=1}^8 \beta_j h_{jt}.$$

For all other days, the Fed funds rate is written as

$$(4.5) \quad E(i_t | I_{t-1}) = i_{t-1} + \phi_1 r_{t-1} + \phi_2 r_{t-2} + \cdots + \phi_r r_{t-r} + \sum_{s=2}^{10} \eta_s d_{st} + \sum_{j=1}^8 \beta_j h_{jt},$$

where d_{st} for $s=2,3,\dots,10$ is a dummy variable that equals 1 if day t is the s th day of the reserve maintenance period. For example, $d_{2t}=1$ if day t is the second day of a maintenance period, or the first Friday, and $d_{2t}=0$ otherwise. The variable d_{10t} takes the value 1 for the last day of a maintenance period, a settlement Wednesday, and equals 0 otherwise. The variable h_{jt} for $j=1,2,\dots,8$ is also a dummy variable to denote U.S. holidays and the last day of a quarter. The dummy variable h_{1t} is equal to 1 if day t precedes a one-day holiday and 0 otherwise. Similarly, h_{2t} is the holiday dummy variable, which is equal to one on a day preceding a three-day holiday and zero on other days. The dummy variables h_{5t} through h_{8t} denote the last day of a quarter. The definitions of d_{st} and h_{jt} are denoted in Table 3 and Table 4.

With the identity (4.1), if the Fed funds rate is affected by lagged Fed funds rates, lagged overnight Eurodollar rates and calendar days such as the day of a two-week reserve maintenance period, U.S. holidays and the last day of a quarter, then those variables also matter for r_t or er_t . It is reasonable to model the overnight Eurodollar rate as explained by lagged Fed funds rates, lagged overnight Eurodollar rates and all the dummy variables. The conditional mean of the overnight Eurodollar rate is estimated by two separate equations because the expected Fed funds rates have different specifications depending on which day of

a two-week reserve maintenance period day t corresponds to and whether day t is the first day of a quarter. On the first day of a maintenance period or the first day of a quarter, the following bivariate model gives the conditional mean of the overnight Eurodollar rate:

$$(4.6) \quad E(r_t | I_{t-1}) = a_1 i_{t-1} + a_2 i_{t-2} + \cdots + a_r i_{t-r} + b_1 r_{t-1} + b_2 r_{t-2} + \cdots + b_s r_{t-s} + \dot{\eta}_1 + \sum_{j=1}^8 \dot{\beta}_j h_{jt}.$$

On other days, it is specified as

$$(4.7) \quad E(r_t | I_{t-1}) = c_1 i_{t-1} + c_2 i_{t-2} + \cdots + c_u i_{t-u} + k_1 r_{t-1} + k_2 r_{t-2} + \cdots + k_w r_{t-w} + \sum_{s=2}^{10} \dot{\eta}_s d_{st} + \sum_{j=1}^8 \dot{\beta}_j h_{jt}.$$

The definitions of dummy variables, d_{st} and h_{jt} , are same as the previous definitions in equations (4.4) and (4.5).

The excess return er_t is treated as the residual variable in the identity (4.1). When I have specified the determinants of i_t and r_t , the equation for er_t is redundant and does not contain any additional information. The conditional mean of the excess return can be calculated by equations (4.2) and (4.4) through (4.7). If there is no friction between the two markets and funds in the two markets are perfectly substitutable, the excess return is not predictable. Since only a small number of banks among U.S. banks can participate in the overnight Eurodollar market, the excess return could be forecastable.

I allow the error terms of equations (4.4) through (4.7) to be heteroskedastic.

$$(4.8) \quad y_t = E(y_t | I_{t-1}) + \sigma_t v_t,$$

where y_t denotes the dependent variable, the Fed funds rate or the overnight Eurodollar rate.

The conditional variance σ_t^2 is a function of date t , lagged Fed funds rates and lagged overnight Eurodollar rates and v_t is a zero-mean, i.i.d. random variable. To capture the frequent small changes and infrequent large changes, which imply high kurtosis, I assume that v_t has a mixture of Normal distributions given by (4.9) below as Hamilton (1996) suggested.

The innovation v_t is drawn from a $N(0,1)$ distribution with probability p and from a $N(0, \tau^2)$

distribution, which has a different variance, with a probability (1-p). The density of mixture of two Normal distributions is

$$(4.9) \quad g(v_t; \underline{\theta}) = \frac{p}{\sqrt{2\pi}} \exp\left(-\frac{v_t^2}{2}\right) + \frac{1-p}{\tau\sqrt{2\pi}} \exp\left(-\frac{v_t^2}{2\tau^2}\right)$$

where $\underline{\theta}$ is a vector of population parameters that includes p and τ^2 . The conditional variance of this distribution is given by

$$(4.10) \quad E\{[y_t - E(y_t | I_{t-1})]^2 | I_{t-1}\} = \sigma_t^2 [p + (1-p)\tau^2].$$

I modified Nelson's (1991) exponential GARCH (EGARCH) model for the log of conditional variance of y_t . I accept hypotheses that GARCH effects are integrated and ξ_s has the same value for day 2 to day 7:

$$(4.11) \quad \xi_2 = \xi_3 = \dots = \xi_7.$$

I also accept the hypothesis of Hamilton (1996) that the most important determinants of the conditional variance are (1) the deviation of the log of conditional variance from its unconditional expectation on the previous day and (2) the average difference between the log of the conditional variance and its unconditional expectation during the previous two-week maintenance period. Hence the log of conditional variance is

$$(4.12) \quad \begin{aligned} \ln(\sigma_t^2) - \sum_{s=1}^{10} \xi_s d_{st} - \sum_{j=1}^8 \kappa_j h_{jt} &= \delta \left[\ln(\sigma_{t-1}^2) - \sum_{s=1}^{10} \xi_s d_{s,t-1} - \sum_{j=1}^8 \kappa_j h_{j,t-1} \right] \\ &+ (1-\delta) \frac{1}{10} \sum_{m=b_t}^{l_t} \left[\ln(\sigma_m^2) - \sum_{s=1}^{10} \xi_s d_{sm} - \sum_{j=1}^8 \kappa_j h_{jm} \right] \\ &+ \alpha [q(v_{t-1}) - Eq(v_{t-1}) + \aleph v_{t-1}], \end{aligned}$$

where b_t and l_t are the beginning and the ending days of the previous maintenance period

respectively. The unconditional expectation of $\ln \sigma_t^2$ equals $\sum_{s=1}^{10} \xi_s d_{st} - \sum_{j=1}^8 \kappa_j h_{jt}$. A

positive value of $(\alpha \cdot \aleph)$ indicates that volatility in conditional variance tends to rise when innovations of y_t are positive. Because of the nondifferentiability of the likelihood function

at $v_{t-1} = 0$ when I numerically maximized the likelihood, $q(v_{t-1})$ takes the following form as Hamilton (1997) suggested:

$$(4.13) \quad q(v_{t-1}) = \begin{cases} (1 + v_{t-1}^2)/2 & \text{for } |v_{t-1}| < 1 \\ |v_{t-1}| & \text{for } |v_{t-1}| \geq 1. \end{cases}$$

This function is differentiable everywhere including $v_{t-1} = 0$. The expected value of $q(v_{t-1})$ is calculated by numerically integrating $q(v_{t-1})$ with its density in (4.9) with respect to v_{t-1} .

Since

$$(4.14) \quad y_t = E(y_t | I_{t-1}) + \sigma_t v_t = \phi(v_t),$$

the conditional density of y_t would be

$$(4.15) \quad f(y_t | I_{t-1}) = g(v_t) \left| \frac{dv_t}{dy_t} \right|$$

where

$$(4.16) \quad v_t = \phi^{-1}(y_t) = [y_t - E(y_t | I_{t-1})] / \sigma_t.$$

$E(y_t | I_{t-1})$ is specified in (4.4) through (4.7). Hence the log of the density is

$$(4.17) \quad \ln f(y_t | I_{t-1}) = \ln[g(v_t)] - \ln(\sigma_t^2)/2.$$

Maximum likelihood estimates are calculated by maximizing the conditional log likelihood with respect to the population parameters subject to two constraints, $0 \leq p \leq 1$ and $\tau^2 > 0$.

V. Empirical Results

The maximum likelihood estimates of the Fed funds rate and the overnight Eurodollar rate are reported in Tables 3 through 7. If day t is the first day of a maintenance period or the first day of a quarter, then the conditional mean of the Fed funds rate is as follows:

(5.1)

$$E(i_t | I_{t-1}) = 0.167 i_{t-1} + 0.079 i_{t-2} + 0.144 i_{t-3} - 0.064 r_{t-1} + 0.439 r_{t-2} + 0.246 r_{t-3} \\ (0.019) \quad (0.047) \quad (0.043) \quad (0.035) \quad (0.080) \quad (0.055) \\ + \eta_1 + \sum_{j=1}^8 \beta_j h_{jt},$$

where the numbers in parentheses are the standard errors. For other typical days, the conditional mean is estimated as

$$(5.2) \quad E(i_t | I_{t-1}) = i_{t-1} + \sum_{s=2}^{10} \eta_s d_{st} + \sum_{j=1}^8 \beta_j h_{jt}.$$

The hypothesis, $H_0 : \phi_1 = \phi_2 = \dots = \phi_r = 0$ in equation (4.5), is not rejected and none of lagged overnight Eurodollar rates are significant in the equation (5.2). The overnight Eurodollar rates can help predict the Fed funds rate only for the first day of a new period and not for any other days. The value η_s for $s = 2, 3, \dots, 10$ can be interpreted as the average change in the Fed funds rate between day s and $s - 1$ as in Hamilton (1996). For example, η_2 equals the average change in the Fed funds rate between first Thursday and first Friday. The maximum likelihood estimates of η_s and β_j are given in Table 3 and Table 4. The second columns of Table 3 and Table 4 show the maximum likelihood estimates of the Fed funds rate specification in Hamilton (1996) and the third columns are the maximum likelihood estimates of the Fed funds rate equation in my model. The effects of day of a reserve maintenance period and holidays on the conditional mean of the Fed funds rate are very similar to Hamilton (1996) except η_1 which is not significant. The main patterns in Hamilton (1996) are found in my study. The Fed funds rate tends to decrease until second Friday of a maintenance period. The Fed funds rate has tendencies to fall on Fridays (η_2 and η_7), Tuesday (η_4 and η_9) and the day before a three-day holiday (β_2) and to rise on Mondays (η_3 and η_8) and day after a one-day or a three-day holiday (β_3 and β_4). It rapidly rises on settlement Wednesday (η_{10}). Note that even though its value is positive in both models, the parameter β_3 was not significant in Hamilton (1996) but significant in my

results. The effect of the last day of a quarter is quite different between the two studies. The end-of-quarter and the end-of-year effects on the conditional mean of the Fed funds rate were not significant in Hamilton (1996), but these effects are very large and significant in this paper. However, the last-day-of-a-year effect on the conditional mean of the Fed funds rate is negligible because when I re-estimated regression equations (4.4) and (4.5) with the new dummy variable, h_{5t}^* , which takes 1 if day t is the last day of the 1st, 2nd or 3rd quarter (not the last day of 4th quarter) and 0 otherwise, the effect of h_{5t}^* is significant but the coefficient of h_{6t} , a dummy variable to indicate the last day of a year, is not significant ($\beta_5 + \beta_6 = -0.098$). The Fed funds rate increases about 34 basis points on the last day of 1st, 2nd or 3rd quarter over other days in my model on an average.

For the first day of a reserve maintenance period or the first of a quarter, the expected overnight Eurodollar rate is described by

(5.3)

$$E(r_t | I_{t-1}) = 0.072i_{t-1} + 0.138i_{t-2} + 0.087i_{t-3} + 0.066r_{t-1} + 0.364r_{t-2} + 0.268r_{t-3} \\ (0.012) \quad (0.038) \quad (0.034) \quad (0.033) \quad (0.077) \quad (0.052) \\ + \dot{\eta}_1 + \sum_{j=1}^8 \dot{\beta}_j h_{jt}.$$

For other days, it is

$$E(r_t | I_{t-1}) = 0.399i_{t-1} - 0.038i_{t-2} - 0.026i_{t-3} + 0.606r_{t-1} + 0.055r_{t-3} \\ (0.015) \quad (0.009) \quad (0.007) \quad (0.017) \quad (0.009) \\ + \sum_{s=2}^{10} \dot{\eta}_s d_{st} + \sum_{j=1}^8 \dot{\beta}_j h_{jt}.$$

The Fed funds rates can help predict the overnight Eurodollar rate on any day of a maintenance period. It might be because i_{t-1} has more information than r_{t-1} . The effect of lagged Fed funds rates on the overnight Eurodollar rate is bigger for days other than the first day of a new period, which is contrasted with the conditional mean of the Fed funds rate. It might be because LIBOR is quoted before the Fed funds markets are opening in the U.S., so yesterday's Fed funds rate has more information than yesterday's LIBOR. The fourth

columns of Table 3 and of Table 4 indicate the values for dummy variables, $\dot{\eta}_s$ and $\dot{\beta}_j$ of equations (5.3) and (5.4) for $s = 1, 2, \dots, 10$ and $j = 1, 2, \dots, 8$ which indicate the day of a reserve maintenance period, U.S. holidays and the last day of a quarter. Except $\dot{\eta}_6$, all estimated parameters for the conditional mean of the overnight Eurodollar rate which are significant at any conventional levels have the same signs as the coefficients of the conditional mean of the Fed funds rate. The absolute values of coefficients of the overnight Eurodollar rate are a little smaller in general but a few of them ($\dot{\eta}_{10}, \dot{\beta}_4, \dot{\beta}_5$ and $\dot{\beta}_6$) are quite different in magnitude from those of the Fed funds rate ($\eta_{10}, \beta_4, \beta_5$ and β_6). The effects of calendar days on the Fed funds rate also exist in the overnight Eurodollar rate. The overnight Eurodollar rate upsurges on the last day of the 1st, 2nd, 3rd or 4th quarter but the Fed funds rate increases in huge amount on the last day of 1st, 2nd or 3rd quarter. To test hypotheses, $H_0 : \eta_s = \dot{\eta}_s$ and $\beta_j = \dot{\beta}_j$, I can test $H_0 : \Delta\eta_s = 0$ and $\Delta\beta_j = 0$ in following (5.5) and (5.6).

Since I treat the excess return as the residual, its conditional mean can be calculated by equations (5.1) through (5.4). If day t is the first day of a maintenance period or the first day of a quarter, then the conditional mean of the excess return is calculated by subtracting (5.1) from (5.3):

$$(5.5) \quad E(er_t | I_{t-1}) = -0.095i_{t-1} + 0.059i_{t-2} - 0.057i_{t-3} + 0.13r_{t-1} - 0.075r_{t-2} + 0.022r_{t-3} \\ + \Delta\eta_1 + \sum_{j=1}^8 \Delta\beta_j h_{jt}.$$

On a typical day, it is calculated by subtracting (5.2) from (5.4):

$$(5.6) \quad E(er_t | I_{t-1}) = -0.601i_{t-1} - 0.038i_{t-2} - 0.026i_{t-3} + 0.606r_{t-1} + 0.055r_{t-3} \\ + \sum_{d=2}^{10} \Delta\eta_d d_t + \sum_{j=1}^8 \Delta\beta_j h_{jt},$$

where $er_t = r_t - i_t$, $\Delta\eta_s = \dot{\eta}_s - \eta_s$ and $\Delta\beta_j = \dot{\beta}_j - \beta_j$. If $\Delta\eta = 0$ and $\Delta\beta_j = 0$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, \dots, 8$, there is no calendar effect on the excess return, and the calendar effects on the overnight Eurodollar rate mirror those of the Fed funds rate. The values of some parameters of equations (5.5) and (5.6) are very big relative to others, so I want to check which ones are significant. To do that, I regressed the excess return on the same explanatory variables. On the first day of a maintenance period or the first day of a quarter, the estimated excess return is as follows:

$$(5.5)' \quad E(er_t | I_{t-1}) = -0.045i_{t-1} + 0.149r_{t-1} - 0.117r_{t-2} + \hat{\Delta\eta}_1 + \sum_{j=1}^8 \hat{\Delta\beta}_j h_{jt} .$$

(0.017) (0.022) (0.021)

On other typical days, it is

$$(5.6)' \quad E(er_t | I_{t-1}) = -0.478i_{t-1} + 0.475r_{t-1} + \sum_{s=2}^{10} \hat{\Delta\eta}_s d_{st} + \sum_{j=1}^8 \hat{\Delta\beta}_j h_{jt} .$$

(0.019) (0.019)

The maximum likelihood estimates of the values for $\hat{\Delta\eta}_s$ and $\hat{\Delta\beta}_j$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, \dots, 8$ are reported in the fifth columns of Table 3 and Table 4. There are some minor discrepancies between the values of calculated coefficients in (5.5) and (5.6) and the estimated ones in (5.5)' and (5.6)' because the equations (5.1) through (5.4), (5.5)' and (5.6)' are estimated by maximum likelihood estimates. The coefficients of i_{t-1} , r_{t-1} and r_{t-2} among lagged interest rates are biggest in (5.5) and statistically significant in (5.5)' if day t is the first day of a maintenance period or the first day of a quarter. The coefficients of i_{t-1} and r_{t-1} are largest in (5.6) and statistically significant in (5.6)' on other days. Even though the values of the coefficients on the conditional mean of the excess return are a little different between the calculated values and the estimated ones, I accept equations (5.5)' and (5.6)' as the model for the excess return because I prefer parsimonious specification. Since the coefficient of i_{t-1} and that of r_{t-1} are almost the same in equation (5.6)', I can use an AR(1)

process to describe the conditional mean of the excess return on a day other than the first day of a maintenance period or the first day of a quarter:

$$(5.6)'' \quad E(er_t | I_{t-1}) = 0.48 er_{t-1} + \sum_{s=2}^{10} \hat{\Delta\eta}_s d_{st} + \sum_{j=1}^8 \hat{\Delta\beta}_j h_{jt}.$$

The value of AR(1) coefficient is positive, meaning the positive correlation between er_t and er_{t+1} . The excess return is predictable on the basis of the previous excess return and dummy variables. Several papers have allowed lagged stock excess returns to be independent variables of the stock excess return with the theoretical reason being discontinuous trading in the stocks making up the index (Scholes and Williams, 1997; Lo and MacKinlay, 1988; and Nelson, 1991). The Scholes and Williams (1977) model proposed an MA(1) process for index returns, while the Lo and MacKinlay (1988) and Nelson (1991) models suggested an AR(1) process. Canova and Marrinan (1995) empirically found that there is some weak positive serial correlation in excess returns between several financial markets.

I also want to know whether calendar day effects are equal for the conditional mean of the overnight Eurodollar rate and for that of the Fed funds rate. If $\dot{\eta}_s = \eta_s$ and $\dot{\beta}_j = \beta_j$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, \dots, 8$, then $\hat{\Delta\eta}_s = 0$ and $\hat{\Delta\beta}_j = 0$, so that these dummy variables do not matter for the conditional mean of the excess return. Remember that $\Delta\eta_s = \dot{\eta}_s - \eta_s$ and $\Delta\beta_j = \dot{\beta}_j - \beta_j$. I strongly reject the null hypothesis, $H_0 : \Delta\eta_s = \Delta\beta_j = 0$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, \dots, 8$. The significant coefficients of $\Delta\eta_s$ and $\Delta\beta_j$ mean that the calendar days matter for the conditional mean of the excess return. As Table 3 and Table 4 show, the calendar day effects on the conditional mean of the overnight Eurodollar rate have same signs as those of the Fed funds rate but the absolute magnitudes of calendar day effects on the conditional mean of the overnight Eurodollar rate are less than those of the Fed funds rate with an exception of η_1 , the first Thursday dummy and η_6 , the second Thursday dummy. Neither η_1 nor $\dot{\eta}_1$ is significant while the negative value of $\hat{\Delta\eta}_1$

is significant. Thus $\dot{\eta}_1 < \eta_1$ even though η_1 and $\dot{\eta}_1$ are not significant. On the settlement Wednesday, the average effect of the day of a maintenance period on the overnight Eurodollar rate is dramatically smaller than that on the Fed funds rate. If day t follows a one-day holiday or a three-day holiday, the holiday effect is much stronger in the Fed funds market than in the overnight Eurodollar market. There are no anticipated different effects of the end of a quarter between the two overnight financial markets.

Recall that the overnight London Interbank Offer Rate (LIBOR) is used for the overnight Eurodollar rate. Thus it does not bounce between the bid and asked rate and is not changed by the composition of borrowers. The maximum likelihood estimates of dummy variables of the conditional mean for the Fed funds rate in this paper are very similar to those in Hamilton (1996). The overnight Eurodollar rate shows very similar calendar day effects with slightly smaller absolute magnitudes. These results give support to the theory that the calendar day effects of the Federal funds rate and the overnight Eurodollar rate are caused at least partly by line limits, transaction costs and weekend accounting convention in the Federal funds market.

The predictability in the differential between the Fed funds rate and the overnight Eurodollar rate can be interpreted in two different ways. One interpretation is that a bank can make a profit on average by the predictability. When it expects that the overnight LIBOR at 11:00 a.m. GMT will be lower than the Fed funds rate, it can borrow the overnight Eurodollar at a foreign branch of U.S. bank (while U.S. banks are close), and sell the funds in the Fed funds market. The converse holds if the LIBOR is expected to be higher than the Fed funds rate. The efficient market hypothesis states that a market is efficient with respect to the information set if it is impossible to make a profit by trading on the basis of the information set (Jensen, 1978). Therefore, this predictability violates the efficient market hypothesis.

The second interpretation is that it does not contradict the efficient market hypothesis. A U.S. bank can predict the differential between the effective Fed funds rate and the overnight LIBOR. The overnight LIBOR is a reference rate, so Eurodollar bank loans are priced at a spread to the LIBOR and a bank has to pay some margin over it to borrow. The

overnight Eurodollar rate can also change form the LIBOR over time. The predictability in the excess return does not allow a bank to make a profit.

Table 5 and Table 6 describe maximum likelihood estimates of the effects of calendar day dummies on the natural log of σ_t in the Fed funds rate and in the overnight Eurodollar rate. The effect of the day of a maintenance period on the conditional variance of the Fed funds rate is bigger in this study compared to the effects in Hamilton (1996) (ξ_s in $E(i_t | I_{t-1}) > \xi_s$ in Hamilton) and the effects on the overnight Eurodollar rate (ξ_s in $E(i_t | I_{t-1}) > \xi_s$ in $E(r_t | I_{t-1})$). Note that $\dot{\xi}_s$ and $\dot{\kappa}_j$ correspond to ξ and κ_j in (4.11) for the maximum likelihood estimates of the overnight Eurodollar rate. The variances of the Fed funds rate and the overnight Eurodollar rate are a little higher on the first day of a maintenance period than on other days ($\xi_1 > \xi_i$ and $\dot{\xi}_1 > \dot{\xi}_i$ for $i = 2, 3, \dots, 7$) and increase during the last three days of the maintenance period ($\xi_i > \xi_{i-1}$ for $i = 8, 9, 10$ and $\dot{\xi}_i > \dot{\xi}_{i-1}$ for $i = 8, 9, 10$). These properties are consistent with the finding in Hamilton (1996). The variance tends to be larger on settlement Wednesday than other days in the both markets. The difference between the log of σ_t^2 of the Fed funds rate on settlement Wednesday and that on other days is larger than the difference in the case of the overnight Eurodollar rate. The ratio of σ_t^2 of the Fed funds rate on settlement Wednesday to that on a typical day is as follows:

$$(5.7) \quad \exp(\xi_{10} - \xi_2) = \exp(-1.182 + 3.846) = 14.354,$$

and the ratio in case of the overnight Eurodollar rate is

$$(5.8) \quad \exp(\dot{\xi}_{10} - \dot{\xi}_2) = \exp(-3.225 + 4.409) = 3.267.$$

On settlement Wednesday, the conditional variance of the Fed funds rate is 14.4 times larger than on other days and the conditional variance of the overnight Eurodollar rate is 3.3 times as large. The conditional variance also increases in both markets on the last day of a quarter.

The effect of the last day of the year on the log of σ_t for the overnight Eurodollar rate is larger than that on the log of σ_t for the Fed funds rate:

$$(5.9) \quad \kappa_5 + \kappa_6 + \kappa_8 = 2.026 + 0 + 2.410 = 4.436$$

and

$$(5.10) \quad \dot{\kappa}_5 + \dot{\kappa}_6 + \dot{\kappa}_8 = 2.678 + 0 + 2.147 = 4.825.$$

If day t is the last day of the year, the magnitude σ_t^2 of the Fed funds rate is $\exp(4.436) = 84.4$ times larger than other days and in case of the overnight Eurodollar rate, $\exp(4.825) = 124.6$ times. On the other hand, the effect of last day of a quarter other than the last day of a year, i.e. the last day of 1st, 2nd or 3rd quarter, is stronger on the log of σ_t of the Fed funds rate:

$$(5.11) \quad \kappa_5 + \kappa_7 = 2.026 + 1.358 = 3.384$$

and

$$(5.12) \quad \dot{\kappa}_5 + \dot{\kappa}_7 = 2.678 + 0 = 2.678.$$

If day t is the 1st, 2nd or 3rd quarter, the conditional variance of the Fed funds rate is 29.5 times as large as that of a typical day and the conditional variance of the overnight Eurodollar rate 14.6 times. The conditional variances of the Fed funds rate and the overnight Eurodollar rate increase more on the last day of a year than on the last day of 1st, 2nd and 3rd quarter.

Maximum likelihood estimates for the other parameters are presented in Table 7. GARCH features of my models are also very similar to Hamilton (1996). The positive δ implies that the deviation of the log of σ_{t-1}^2 from its unconditional expected value has a positive effect on its current deviation in both markets. Because α is positive in the specifications of the Fed funds rate (the overnight Eurodollar rate), the deviation of the absolute value of previous day's innovation in the Fed funds rate (the overnight Eurodollar rate) from its expected value causes the log of σ_t^2 of the Fed funds rate (the overnight

Eurodollar rate) to be larger. The positive and significant α means that positive shocks increase variance more than negative shocks in both markets.

The innovation v_t is assumed to be drawn from a mixture of two Normal distributions. About 83 percent of Fed funds rate and overnight Eurodollar rate are drawn from distribution 1, a Normal distribution with variance 1. With probability of 0.17, v_t of the Fed funds rate comes from $N(0, 9.87)$. With the same probability, v_t of the overnight Eurodollar rate is drawn from $N(0, 11.7)$. They come from very similar distributions.

VI. Model Comparison

I find a significant effect captured by calendar day dummies, which correspond to a day of the two-week reserve maintenance period, U.S. holidays and the last day of a quarter. I want to evaluate my model compared to other models using in- and out-of-sample performances judged by mean squared error and mean absolute error. The in-sample period runs from March 1, 1984 to November 28, 1990 and the out-of-sample period from November 29, 1990 to March 26, 1997. The reason for choosing November 28, 1990 as the end of the in sample period is that it is the last day of Hamilton's (1996) data set.

Three kinds of models are estimated and the results are displayed in Table 8 and Table 9. My models are denoted as model A and other models, which are compared with model A, are denoted as model B and model C in Table 8 and Table 9. I maintain the hypotheses in section 5: On a day other than the first day of the maintenance period or the first day of a quarter, the Fed funds rate is not affected by lagged overnight Eurodollar rates and the excess return is affected by only the previous excess return among lagged variables. That is, my models follow the restricted forms as seen in Table 8 if day t is not the first day of a new period. If day t is the first day of the maintenance period or the first day of a quarter, they follow autoregressive processes with dummy variables. To investigate the calendar dummy effect on the conditional mean, model B includes only a constant, lagged Fed funds rates and lagged overnight Eurodollar rates in the explanatory variables but none of dummy variables.

I suggest another model for the excess return, model C, which is a white noise process, to test whether lagged overnight rates can forecast the excess return.

Table 8 shows mean squared error and mean absolute error of three models. Except for one case, my models perform better in- and out-of-sample with respect to two accuracy measures: mean squared error and mean absolute error. The exception is the random walk model. The random walk model fits best in-sample for estimating the excess return but it does badly out-of-sample compared to my model and model B.

The two accuracy measures I have conducted are sample estimates of forecast accuracy. I need to test whether my models are statistically better over the post-sample period than the others. I evaluate two test statistics, the Diebold–Mariano test statistic (DM) and the Morgan-Granger-Newbold test statistic (MGN) to test the equal forecast accuracy hypothesis. Table 9 summarizes the results of model comparison.

Consider two forecasts $\{\hat{y}_{it}\}_{t=1}^T$ and $\{\hat{y}_{jt}\}_{t=1}^T$ of the time series $\{y_t\}_{t=1}^T$. Let T be the out of sample size and the associated out of sample forecast errors be $\{e_{it}\}_{t=1}^T$ and $\{e_{jt}\}_{t=1}^T$. The $T \times 1$ vectors e_i and e_j stack the forecast error series. If the loss differential series $\{d_t = g(e_{it}) - g(e_{jt})\}_{t=1}^T$ is covariance stationary, the asymptotic test is proposed by Diebold-Mariano (1995):

$$(6.1) \quad S_1 = \frac{\bar{d}}{\sqrt{\frac{2\pi \hat{f}_d(0)}{T}}} \xrightarrow{d} N(0,1)$$

where $g(\cdot)$ is an arbitrary function of error,

$$(6.2) \quad \bar{d} = \frac{1}{T} \sum_{t=1}^T d_t,$$

and $f_d(0)$ the spectral density of the loss differential at frequency zero

$$(6.3) \quad f_d(0) = \frac{1}{2\pi} \sum_{\tau=-\infty}^{\infty} \left[\frac{1}{T} \sum_{t=|\tau|+1}^T (d_t - \bar{d})(d_{t-|\tau|} - \bar{d}) \right].$$

Since

$$(6.4) \quad 2\pi f_d(0) = C(1)^2 \sigma^2,$$

I use a more convenient statistic:

$$(6.1)' \quad S_1 = \frac{\bar{d}}{\sqrt{\frac{C(1)^2 \sigma^2}{T}}} \xrightarrow{d} N(0,1)$$

where $C(1)$ and σ^2 are defined as follows,

$$(6.5) \quad d_t = \alpha + C(L)\varepsilon_t, \quad \varepsilon_t \sim wn(0, \sigma^2).$$

I calculated $C(1)$ by rewriting $MA(\infty)$ as $AR(p)$ representation with an assumption of invertibility and decided lag p by the Akaike Information Criterion (AIC). The residual variance σ^2 is estimated by

$$(6.6) \quad \hat{\sigma}^2 = \frac{1}{T} \sum_{t=1}^T (\hat{\varepsilon}_t - \bar{\hat{\varepsilon}})^2$$

where

$$(6.7) \quad \hat{\varepsilon}_t = d_t - \hat{d}_t$$

and \hat{d}_t is the fitted value. I consider two forms $g(\cdot)$, quadratic and absolute function.

If loss is quadratic and forecast errors are zero mean, Gaussian and serially uncorrelated, the null hypothesis of equal forecast accuracy is equivalent to zero correlation between x and z where $x = e_i + e_j$ and $z = e_i - e_j$. That is, I test $\rho_{xz} = 0$. To proceed to test $\rho_{xz} = 0$, two types of test statistics for correlation are used and are called z_1 and z_2 .

The statistic z_1 is calculated as follows:

$$(6.8) \quad z_1 = \frac{\hat{\rho}_{xz}}{\sqrt{\frac{1 - \hat{\rho}_{xz}^2}{T-2}}}$$

where

$$(6.9) \quad \hat{\rho}_{xz} = \frac{x'z}{\sqrt{(x'x)(z'z)}}.$$

It follows Student's t distribution with $T - 2$ degrees of freedom. Under the null, the other statistic z_2 for testing the correlation is as follows (Granger and Swanson (1994)),

$$(6.10) \quad z_2 = \frac{\sqrt{T-1}}{2} \log \left(\frac{1 + \hat{\rho}_{xz}}{1 - \hat{\rho}_{xz}} \right) \sim N(0,1).$$

I calculate the loss differential $d_i = g(e_{it}) - g(e_{jt})$, $x = e_i + e_j$ and $z = e_i - e_j$ where i indicates my model and j other two alternative models. Hence the significant negative value of statistic denotes that my model is superior to other models. The forecasting accuracy test results are shown in Table 9. All values but those for the excess return are significantly negative at the 5 percent level. My models are significantly outperformed at a 10 percent level for forecasting the excess return except DM statistic with accuracy measure of the mean squared error. Therefore, I can conclude that my models, which consider calendar day effects, are best performed over the out-of-sample periods.

VII. Conclusion

The Fed funds rate shows a very similar calendar day effect in both Hamilton (1996) and my model. The effects of the calendar day on the Fed funds rate are reflected in the overnight Eurodollar rate but the absolute magnitude of the calendar day effects on the overnight Eurodollar rate is slightly smaller than the effects on the Fed funds rate. The spread between the Fed funds rate and the overnight rate is predictable on the basis of lagged interest rates and calendar day dummies. It suggests the possibility that a bank can make profit by arbitrage between two markets.

The Fed funds rate can help forecast the overnight Eurodollar rate on any day of a maintenance period. On the other hand, the overnight Eurodollar rates help forecast the Fed funds rate if day t is the first day of a new period, but does not help otherwise. These results might come from the fact that two interest rates are measured at different times. The LIBOR is the average rate provided by participants in the British Bankers Association (BBA) and is fixed daily at 11:00 a.m. GMT, which is at 6:00 a.m. EST. The

effective Fed funds rate is a weighted average of Fed funds rates during a day. Therefore, yesterday's Fed funds rate has more information than yesterday's LIBOR.

The forecast accuracy test indicates that my models have the best post-sample performance, compared to other models. However because the forecast accuracy test is not enough to refute the possibility that the presence of calendar effects is induced by data-snooping (Sullivan, Timmermann and White 1998), it is desirable to have a theoretical model to explain this empirical finding. I leave a theoretical model for my future research.

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Table 1. Summary Statistics for the Fed Funds Rate, the Eurodollar Rate and their Differential

	i_t	Δi_t	r_t	Δr_t	er_t
Mean	6.438	-0.001	6.355	-0.001	-0.083
Maximum	16.170	7.790	25.000	13.500	0.650
Minimum	2.580	-7.890	2.750	-17.120	-4.670
Std. Dev.	2.148	0.383	2.140	0.450	0.332
Skewness	0.191	0.170	0.329	-8.188	9.566
Kurtosis	2.557	127.366	4.082	896.240	363.290

1) i_t is the Fed funds rate on day t .

2) $\Delta i_t = i_t - i_{t-1}$.

3) r_t is the overnight Eurodollar rate on day t .

4) $\Delta r_t = r_t - r_{t-1}$.

5) er_t is the excess return on the overnight Eurodollar rate over the Fed funds rate on day t

$$er_t = r_t - i_t.$$

Table 2. Summary Statistics for the Fed Funds Rate, the Eurodollar Rate and their Differential

(Exclude Dec. 31, 1985 and Dec. 30 and Dec. 31, 1986)

	i_t	Δi_t	r_t	Δr_t	er_t
Mean	6.431	-0.001	6.345	-0.001	-0.085
Maximum	12.310	2.830	12.310	2.250	4.470
Minimum	2.580	-2.700	2.750	-2.500	-3.950
Std. Dev.	2.134	0.311	2.112	0.206	0.262
Skewness	0.149	0.688	0.134	-0.594	0.240
Kurtosis	2.402	18.842	2.426	28.070	53.502

1) i_t is the Fed funds rate on day t .

2) $\Delta i_t = i_t - i_{t-1}$.

3) r_t is the overnight Eurodollar rate on day t .

4) $\Delta r_t = r_t - r_{t-1}$.

5) er_t is the excess return on the overnight Eurodollar rate over the Fed funds rate on day t

$$er_t = r_t - i_t.$$

Table 3. Maximum Likelihood Estimates of the Conditional Mean
(day of the reserve maintenance period effects)

	Hamilton (1996)	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$	$E(er_t I_{t-1})$
s	η_s	η_s	$\dot{\eta}_s$	$\Delta\eta_s$
1	0.018* (0.008)	-0.007 (0.018)	-0.017 (0.016)	-0.037* (0.017)
2	-0.040* (0.002)	-0.060* (0.005)	-0.032* (0.006)	0.009 (0.008)
3	0.041* (0.007)	0.056* (0.005)	0.028* (0.005)	-0.057* (0.007)
4	-0.036* (0.006)	-0.053* (0.004)	-0.012* (0.005)	0.030* (0.007)
5	-0.036* (0.006)	-0.033* (0.004)	-0.011* (0.005)	0.007 (0.006)
6	0.008 (0.006)	0.011* (0.004)	-0.017* (0.005)	-0.043* (0.006)
7	-0.034* (0.006)	-0.042* (0.004)	-0.023* (0.005)	0.009 (0.008)
8	0.057* (0.008)	0.080* (0.006)	0.045* (0.006)	-0.049* (0.008)
9	-0.045* (0.009)	-0.060* (0.007)	0.004 (0.006)	0.050* (0.008)
10	0.139* (0.023)	0.137* (0.016)	0.052* (0.007)	-0.107* (0.019)

1) The value s indicates which day of a two-week reserve maintenance period day t falls on.

- $s = 1$ indicates that day t is first Thursday.
- $s = 2$ indicates that day t is first Friday.
- $s = 3$ indicates that day t is first Monday.
- $s = 4$ indicates that day t is first Tuesday.
- $s = 5$ indicates that day t is first Wednesday.
- $s = 6$ indicates that day t is second Thursday.
- $s = 7$ indicates that day t is second Friday.
- $s = 8$ indicates that day t is second Monday.
- $s = 9$ indicates that day t is second Tuesday.
- $s = 10$ indicates that day t is second Wednesday.

The value η_s is the maximum likelihood estimate of coefficient of d_{st} on the conditional mean.

2) Standard errors are in parenthesis.

3) * denotes rejection of the null hypothesis at 5% level

Table 4. Maximum Likelihood Estimates of the Conditional Mean
(U.S. holiday and the last day of a quarter effects)

	Hamilton (1996)	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$	$E(er_t I_{t-1})$
j	β_j	β_j	$\dot{\beta}_j$	$\Delta\beta_j$
1	-0.028 (0.020)	-0.027 (0.024)	-0.003 (0.015)	0.026 (0.025)
2	-0.031* (0.011)	-0.024* (0.008)	-0.008 (0.008)	0.015 (0.011)
3	0.023 (0.020)	0.065* (0.021)	-0.021 (0.014)	-0.097* (0.020)
4	0.171* (0.017)	0.198* (0.011)	0.069* (0.009)	-0.161* (0.012)
5	{0.000}	0.340* (0.078)	0.242* (0.054)	-0.120 (0.095)
6	{0.000}	-0.439* (0.192)	-0.052 (0.112)	0.048 (0.273)
7	{0.000}	0.026 (0.021)	-0.011 (0.012)	-0.029 (0.027)
8	{0.000}	-0.046 (0.052)	0.027 (0.031)	0.037 (0.020)

- 1) $j = 1$ indicates that day t precedes a one-day holiday.
 $j = 2$ indicates that day t precedes a three-day holiday.
 $j = 3$ indicates that day t follows a one-day holiday.
 $j = 4$ indicates that day t follows a three-day holiday.
 $j = 5$ indicates that day t is the last day of 1st, 2nd, 3rd or 4th quarter.
 $j = 6$ indicates that day t is the last day of the year.
 $j = 7$ indicates that day t is one day before, on or one day after last day of 1st, 2nd, 3rd or 4th quarter.
 $j = 8$ indicates that day t is two days before, one day before, on, one day after or two days after the end of the year.

β_j is the maximum likelihood estimate of h_{jt} on the conditional mean.

- 2) Standard errors are in parenthesis.
3) * denotes rejection of the null hypothesis at 5% level
4) { } indicates the restricted value.

Table 5. Maximum Likelihood Estimates of the Conditional Variance
(day of the reserve maintenance period effects)

	Hamilton (1996)	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$
s	ξ_s	ξ_s	$\dot{\xi}_s$
1	-4.233* (0.704)	-3.464* (0.411)	-3.487* (0.534)
2	-4.761* (0.675)	-3.846* (0.401)	-4.409* (0.545)
3	{-4.761}	{-3.846}	{-4.409}
4	{-4.761}	{-3.846}	{-4.409}
5	{-4.761}	{-3.846}	{-4.409}
6	{-4.761}	{-3.846}	{-4.409}
7	{-4.761}	{-3.846}	{-4.409}
8	-4.258* (0.691)	-3.103* (0.408)	-3.985* (0.558)
9	-3.846* (0.701)	-2.839* (0.417)	-3.956* (0.543)
10	-1.986* (0.689)	-1.182* (0.414)	-3.225* (0.551)

1) The value s indicates which day of a two-week reserve maintenance period day t falls on.

- $s = 1$ indicates that day t is first Thursday.
- $s = 2$ indicates that day t is first Friday.
- $s = 3$ indicates that day t is first Monday.
- $s = 4$ indicates that day t is first Tuesday.
- $s = 5$ indicates that day t is first Wednesday.
- $s = 6$ indicates that day t is second Thursday.
- $s = 7$ indicates that day t is second Friday.
- $s = 8$ indicates that day t is second Monday.
- $s = 9$ indicates that day t is second Tuesday.
- $s = 10$ indicates that day t is second Wednesday.

The value ξ_s is the maximum likelihood estimate of coefficient of d_{st} on the conditional mean.

2) Standard errors are in parenthesis.

3) * denotes rejection of the null hypothesis at 5% level

Table 6. Maximum Likelihood Estimates of the Conditional Variance
(holiday and the last day of a quarter effects)

	Hamilton (1996)	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$
j	κ_j	κ_j	$\dot{\kappa}_j$
1	{0.000}	{0.000}	{0.000}
2	{0.000}	{0.000}	{0.000}
3	{0.000}	{0.000}	{0.000}
4	{0.000}	{0.000}	{0.000}
5	0.853* (0.379)	2.020* (0.258)	2.658* (0.331)
6	0.975 (0.765)	-0.739 (0.521)	-0.655 (0.725)
7	1.550* (0.216)	1.353* (0.195)	0.332 (0.223)
8	{1.550}	2.434* (0.255)	2.148* (0.344)

- 1) $j = 1$ indicates that day t precedes a one-day holiday.
 $j = 2$ indicates that day t precedes a three-day holiday.
 $j = 3$ indicates that day t follows a one-day holiday.
 $j = 4$ indicates that day t follows a three-day holiday.
 $j = 5$ indicates that day t is the last day of 1st, 2nd, 3rd or 4th quarter.
 $j = 6$ indicates that day t is the last day of the year.
 $j = 7$ indicates that day t is one day before, on or one day after last day of 1st, 2nd, 3rd or 4th quarter.
 $j = 8$ indicates that day t is two days before, one day before, on, one day after or two days after the end of the year.
- β_j is the maximum likelihood estimate of h_{jt} on the conditional mean.
- 2) Standard errors are in parenthesis.
- 3) * denotes rejection of the null hypothesis at 5% level
- 4) {·} indicates the restricted value.

Table 7. Maximum Likelihood Estimates of Other Parameters

Parameters	Hamilton (1996)	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$
δ	0.793* (0.046)	0.486* (0.043)	0.595* (0.061)
α	0.316* (0.036)	0.469* (0.029)	0.339* (0.031)
\aleph	0.341* (0.083)	0.196* (0.043)	0.128* (0.045)
p	0.861* (0.026)	0.832* (0.014)	0.831* (0.016)
τ^2	8.497* (1.165)	9.870* (0.741)	11.703* (0.856)

1) The maximum likelihood estimates maximize the following log likelihood for T = 3279,

$$L = \sum_{t=2}^T \ln f(v_t | I_{t-1}) = \sum_{t=2}^T (\ln[g(v_t)] - \ln(\sigma_t^2)/2)$$

where

$$g(v_t; \underline{\theta}) = \frac{p}{\sqrt{2\pi}} \exp\left(\frac{-v_t^2}{2}\right) + \frac{1-p}{\tau\sqrt{2\pi}} \exp\left(\frac{-v_t^2}{2\tau^2}\right)$$

and

$$\begin{aligned} \ln(\sigma_t^2) - \sum_{s=1}^{10} \xi_s d_{st} - \sum_{j=1}^8 \kappa_j h_{jt} = & \delta \left[\ln(\sigma_{t-1}^2) - \sum_{s=1}^{10} \xi_s d_{s,t-1} - \sum_{j=1}^8 \kappa_j h_{j,t-1} \right] \\ & + (1-\delta) \frac{1}{10} \sum_{m=b_t}^{l_t} \left[\ln(\sigma_m^2) - \sum_{s=1}^{10} \xi_{s_m} d_{sm} - \sum_{j=1}^8 \kappa_j h_{jm} \right] \\ & + \alpha [q(v_{t-1}) - Eq(v_{t-1}) + \aleph v_{t-1}]. \end{aligned}$$

2) * denotes rejection of the null hypothesis at 5% level

Table 8. Model Comparison

Model A	<p>1. For the first day of the maintenance period or the first day of a quarter,</p> $y_t = \alpha_1 i_{t-1} + \alpha_2 i_{t-2} + \dots + \alpha_p i_{t-p} + \delta_1 r_{t-1} + \delta_2 r_{t-2} + \dots + \delta_q r_{t-q} + \eta_1 + \sum_{j=1}^8 \beta_j h_{jt} + \sigma_t v_t$ <p>2. For a day other than the first day of the maintenance period or the first day of a quarter,</p> <p>(1) The Fed funds rate, i_t</p> $i_t = i_{t-1} + \sum_{s=2}^{10} \eta_s d_{st} + \sum_{j=1}^8 \beta_j h_{jt} + \sigma_t v_t$ <p>(2) The overnight Eurodollar rate, r_t</p> $r_t = a_1 i_{t-1} + a_2 i_{t-2} + \dots + a_r i_{t-r} + b_1 r_{t-1} + b_2 r_{t-2} + \dots + b_u r_{t-u} + \sum_{s=2}^{10} \dot{\eta}_s d_{st} + \sum_{j=1}^8 \dot{\beta}_j h_{jt} + \sigma_t v_t$ <p>(3) The excess return, er_t</p> $er_t = \lambda er_{t-1} + \sum_{s=2}^{10} \Delta \eta_s d_{st} + \sum_{j=1}^8 \Delta \beta_j h_{jt} + \sigma_t v_t$
Model B	<p>1. For the first day of the maintenance period or the first day of a quarter,</p> $y_t = c + \tau_1 i_{t-1} + \tau_2 i_{t-2} + \dots + \tau_v i_{t-v} + \omega_1 r_{t-1} + \omega_2 r_{t-2} + \dots + \omega_w r_{t-w} + \sigma_t v_t$ <p>2. For a day other than the first day of the maintenance period or the first day of a quarter,</p> <p>(1) The Fed funds rate, i_t</p> $i_t = c + i_{t-1} + \sigma_t v_t$ <p>(2) The overnight Eurodollar rate, r_t</p> $r_t = c + \phi_1 i_{t-1} + \phi_2 i_{t-2} + \dots + \phi_j i_{t-j} + \theta_1 r_{t-1} + \theta_2 r_{t-2} + \dots + \theta_h r_{t-h} + \sigma_t v_t$ <p>(3) The excess return, er_t</p> $er_t = c + \alpha er_{t-1} + \sigma_t v_t$
Model C	<p>The excess return, er_t is a white noise process:</p> $er_t = c + \sigma_t v_t.$

where c is a constant

y_t is the Fed funds rate, the overnight Eurodollar rate or the excess return of the overnight Eurodollar rate over the Fed funds rate.

$\sigma_t v_t$ is defined in section 4.

Mean Squared Error (MSE) and Mean Absolute Error (MAE)					
Series	Model	MSE		MAE	
		In Sample	Out of Sample	In Sample	Out of Sample
i_t	A	0.113	0.071	0.149	0.139
	B	0.121	0.083	0.163	0.158
r_t	A	0.109	0.024	0.109	0.088
	B	0.122	0.026	0.115	0.093
er_t	A	0.144	0.071	0.139	0.136
	B	0.179	0.076	0.154	0.144
	C	0.136	0.084	0.155	0.155

Table 9. Forecasting Accuracy Test

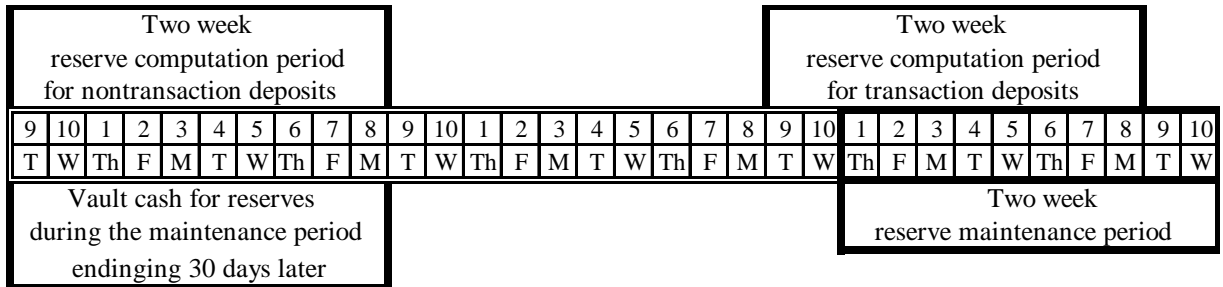
Series	Compared models	Diebold-Mariano test		Morgan-Granger-Newbold test	
		Squared error	Absolute error+	z_1	z_2
i_t	A vs. B	-5.625	-11.123	-11.482	-4.920
r_t	A vs. B	-2.111	-4.221	-5.230	-2.265
er_t	A vs. B	-1.725	-3.230	-4.260	-1.847
	A vs. C	-1.496	-6.870	-8.042	-3.469

1) Model A, B and C are defined in Table 8.

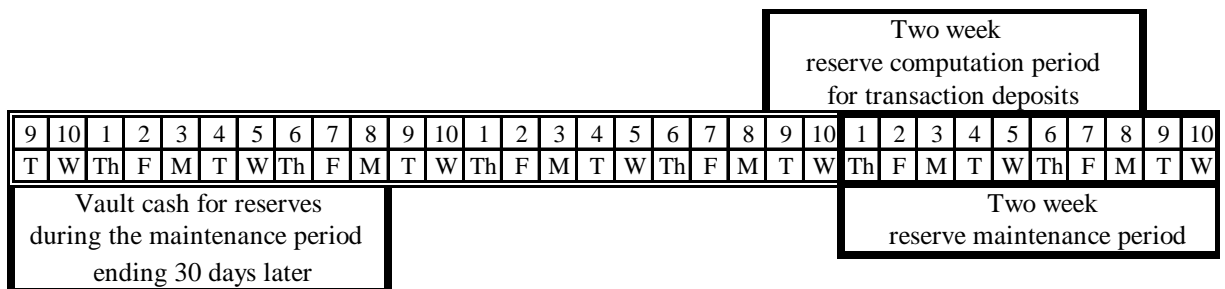
2) The null hypothesis is that there is no difference in the accuracy of two forecasts.

Figure 1

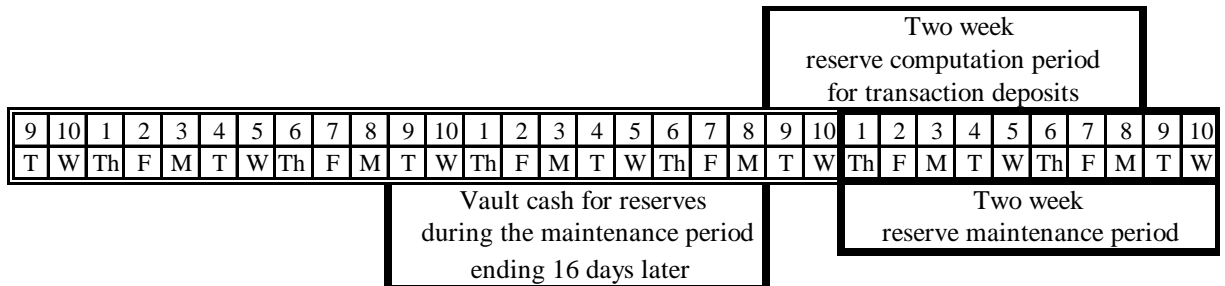
A. Reserve Accounting System (1984 – November, 1990)



B. Reserve Accounting System (December, 1990 – November, 1992)



C. Reserve Accounting System (December, 1992 – 1997)



1, 2, ..., 10 indicates that which day of a two-week reserve maintenance period day t falls on.

1 = the first Thursday of a maintenance period.

2 = the first Friday of a maintenance period.

⋮

10 = the settlement Wednesday of a maintenance period.

Figure 2
Federal Funds Rate

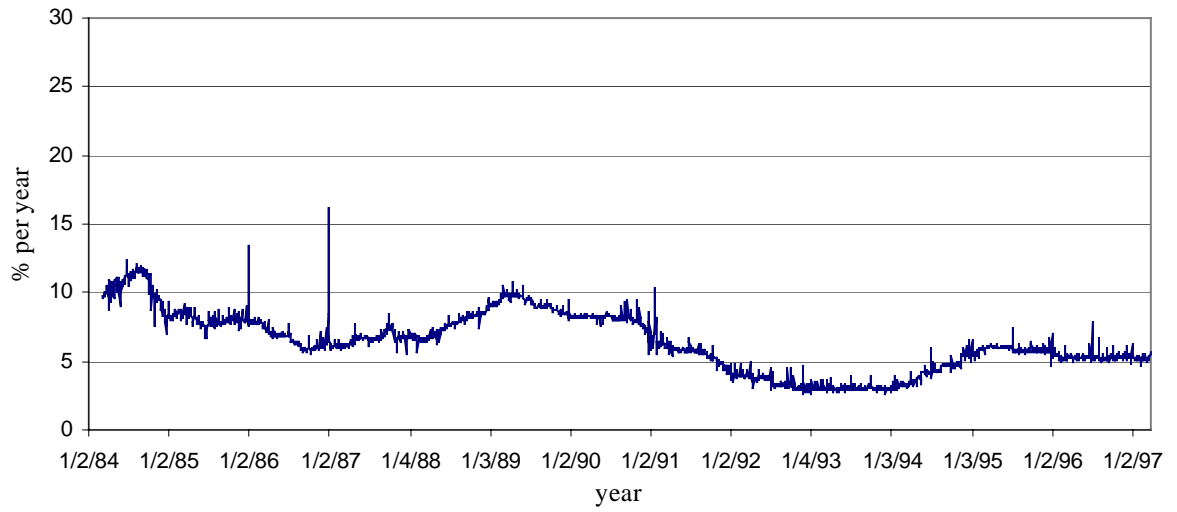


Figure 3
Overnight Eurodollar Rate

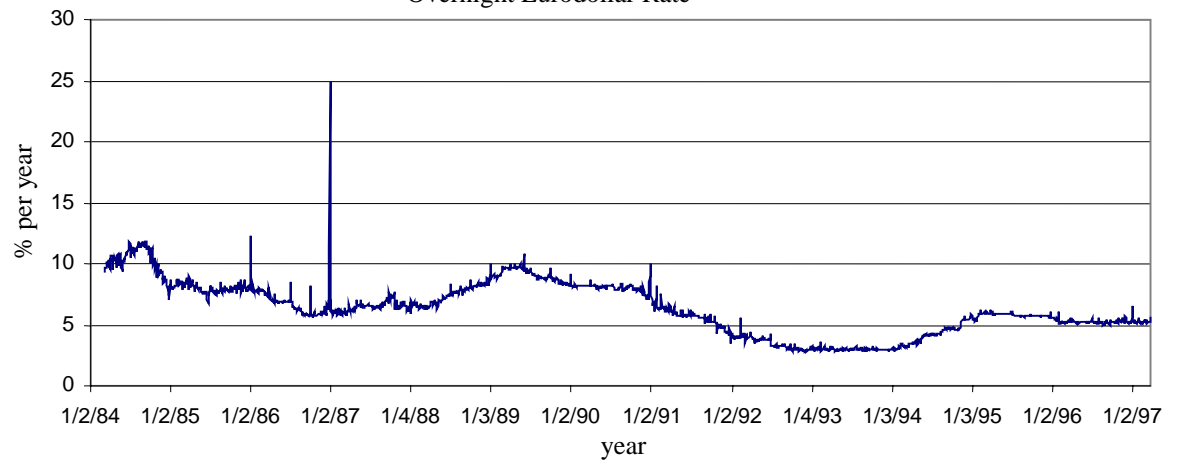
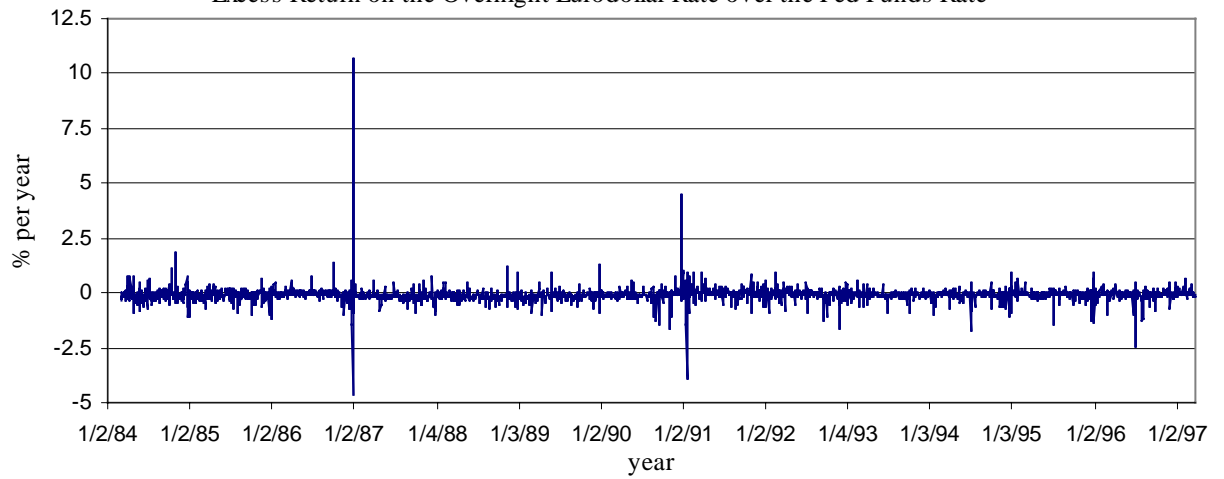


Figure 4
Excess Return on the Overnight Eurodollar Rate over the Fed Funds Rate



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