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Young-Sook Lee is Research Fellow, School of Economics, University of Nottingham

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Young-Sook Lee

School of Economics
University of Nottingham

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Abstract

It has been found in the literature that the overnight Eurodollar rate and the effective Fed funds rate exhibit similar calendar-day effects caused by the Federal reserve regulations and accounting conventions and characteristics of the Fed funds market. However, it was not documented whether the effects are the same on the two interest rates. This paper finds that the effects are smaller on the overnight Eurodollar rate than on the Fed funds rate. Even if the overnight Eurodollar market is affected by the Fed funds market, the overnight Eurodollar market is not perfectly integrated with the Fed funds market.

JEL classification: E43; G15; G21
Keywords: Financial market integration; Overnight Eurodollar rate; Fed funds rate; Calendar-day effects

Dr. Young-Sook Lee
School of Economics
University of Nottingham
University Park
Nottingham, NG7 2RD
U.K.
Tel) 0115 846 6715
Fax) 0115 951 4159
E-mail) young-sook.lee@nottingham.ac.uk

I. Introduction

This paper closely investigates the relationship between the overnight Eurodollar rate and the Fed funds rate. Lee (2003) finds that the overnight Eurodollar rate and the effective Fed funds rate exhibit similar calendar-day effects but the calendar-day effects on the overnight Eurodollar rate are smaller than those on the effective Fed funds rate. The overnight Eurodollar rate and the effective Fed funds rate tend to fall during the two-week maintenance period until second Fridays. They decrease on Fridays and increase on Mondays, after U.S. holidays and on settlement Wednesdays. The conditional variances of the Fed funds rate and the overnight Eurodollar rate have a tendency to increase as settlement Wednesdays approach and are highest on settlement Wednesdays. These results indicate that the overnight Eurodollar rate is affected by Federal Reserve regulations and U.S. reserve accounting conventions even if some participants in the overnight Eurodollar market do not hold reserves in the U.S. to meet reserve requirements over the reserve maintenance period and do not trade in the Fed funds market.

The overnight Eurodollar rate in London and the effective Fed funds rate employed by Lee (2003) are collected at different times: the overnight Eurodollar rate is observed between 7:00 am and 8:00 am Eastern Standard Time (EST) and the effective Federal funds rate is a weighted average of the Federal funds rate from the opening to the closing in the Federal funds market. Spindt and Hoffmeister (1988) provide a model where the variance of the Fed funds rate changes within a day; it becomes higher toward the end of each business day and is highest at the end of settlement Wednesday. Griffiths and Winters (1995) empirically show that the high and low rates of the afternoon Fed funds rate fall significantly over the maintenance period. However, the high and low rates of the morning Fed funds rate tend to fall over the first week and remain statistically unchanged throughout the remainder of the maintenance period. On settlement Wednesdays, the afternoon low rates remain statistically unchanged but the afternoon high rates increase significantly. They also show that the afternoon variances are larger than the morning variances but predictable patterns of their variance changes are very similar. They conclude that the data generating process in the morning is different from the process in the afternoon. Cyree and Winters (2001*a*) find that the largest variance occurs at the open and close of trading. Cyree and Winters (2001*b*) note that daily rate changes and variance patterns differ depending on the time of the rate observations (the morning rate v.s. the closing rate). Based on Spindt and Hoffmeister (1988), Griffiths and Winters (1995) and Cyree and Winters (2001*a* and *b*), the differences between the calendar-day effects on the Fed funds rate and those on the overnight Eurodollar rate might be attributable to the time gap in collecting the two sets of data.

There is some literature investigating joint time series behaviour of asset returns in the Fed funds market and other short-term financial markets in the U.S. Ho and Saunders (1985) develop a model to explain the typically positive spread between the Fed funds rate and other short-term money market rates. Their model assumes that a bank's demand for Fed funds is submitted at a point in time prior to the time when the bank closes its books and that the timing interval is very small. Therefore, the bank can not use other market methods such as Eurodollars, repos and T-bills to adjust reserves. Griffiths and Winters (1997*a*) note that overnight government-backed general collateral repos exhibit daily rate change and daily variance patterns consistent with patterns identified in the Fed funds market. However, the effects of Fed Reserve regulations are less in the government repo market and the overnight government repo rate shows much less effect of settlement Wednesdays and it does not have the effect of second Tuesdays (before settlement Wednesdays). They use daily closing bid side broker quotes for the overnight repo rate and for the overnight Fed funds rate. This discrepancy between the two markets might be caused because lending money through a repo transaction is safer than selling Fed funds because a sale of Fed funds is an unsecured loan while repo transactions are secured by the top-quality paper. Soderstrom (2001) examines the Federal fund market and the Federal funds futures market. The expectations extracted from the futures market do not perform very well in predicting the average funds rate on a daily basis. The futures-based funds rate expectations tend to show some systematic variation across calendar months and during the last days of each month, and adjusting for the monthly variation improves their predictive power. His results indicate that there are systematic inconsistencies between the futures prices and the movements in the average funds rate. The research, such as Ho and Saunders (1985), Griffiths and Winters (1997*a*) and Soderstrom (2001), can be interpreted as evidence to support that the calendar-day effect differences between the effective Fed funds rate and the overnight Eurodollar rate come from market differences.

The existence of smaller calendar-day effects on the overnight Eurodollar rate in London than those on the effective Fed funds rate documented by Lee (2003) could be due to either market differences or to the time difference in collecting the two interest rates. This paper analyzes the hourly Fed funds rates in addition to the effective Fed funds rate and the overnight Eurodollar rate to identify the causes of smaller calendar-day effects on the overnight Eurodollar rate. The results indicate that the predictable calendar-day effect differences are caused mainly by market differences between the Fed funds market and the overnight Eurodollar market. The overnight Eurodollar rate and the Fed funds rate have the systematic calendar-day effect differences even if they are the prices of funds traded at the same time and the effects of reserve accounting conventions and characteristics of the Fed funds market are weaker on the overnight Eurodollar rate than on the Fed funds rate. Even if the overnight Eurodollar rate is affected by the Federal funds market in the U.S., the overnight Eurodollar market is not perfectly united with the Fed funds market.

This paper proceeds as follows. Section II provides a discussion of the institutional details of the Fed funds market and the overnight Eurodollar market. The data are described in Section III. Section IV describes the empirical methodology, and Section V reports the empirical results. The conclusion is presented in Section VI.

II. The Fed funds market and the overnight Eurodollar market

All depository institutions in the U.S. are required to satisfy reserve requirements on deposits. Under contemporaneous reserve accounting, introduced by the Fed in February 1984 and ending in July 1998, the minimum average balance of end-of-day holdings of Federal Reserve deposits over a two-week maintenance period must equal or be bigger than reserve requirements over a two-week computation period, as Figure 1 shows. Required reserves are computed as percentages of deposits over the computation period that banks must hold as vault cash or deposit at the Federal Reserve Bank. For required reserves against transaction deposits, the computation period is the two weeks ending on Monday two days before the maintenance period ends on Wednesday, which is called settlement Wednesday. Thus, required reserves are unknown during the period and must be estimated except on two days. Reserves held on Fridays are counted as balances held for three days and reserves held on the day before a one-day holiday for two days. Depository institutions are allowed to carry over for a maintenance period an excess or deficiency of up to about 2 percent of their required reserves. Depository institutions which fail to meet their reserve requirements are subject to financial penalties. Because the Federal Reserve does not pay interest on reserve accounts, depository institutions want to hold their reserve balances at the minimum level to meet their needs.

To satisfy reserve requirements, a depository institution manages its reserve account balances through lending and borrowing. For a U.S. bank that is short of reserves, borrowing overnight Eurodollars is an alternative to purchasing Fed funds. For a U.S. bank with excess reserves, an overnight Eurodollar deposit is an alternative option to the sale of Fed funds. The Fed funds market is the interbank market for borrowing or lending Fed funds on deposit in a bank's reserve account at the Federal Reserve. Most Fed funds loans are overnight transactions. The eligible participants in the Fed funds market are commercial banks and other depository institutions (savings and loan associations, savings banks, credit unions, and foreign bank branches) that maintain accounts at the Federal Reserve, and federally sponsored agencies that provide banking services in the U.S. and certain official international banking organizations. Eurodollars are U.S. dollar deposits at banking offices in a country outside the U.S. such as London, Tokyo, Hong Kong, Singapore, Western European financial centers, and other parts of the world. U.S. banks are among the major participants in the Eurodollar market with big corporations, central banks, commercial banks of other countries and wealthy individuals. The transactions are unsecured by anything other than verbal agreements both in the Fed funds market and in the Eurodollar market. Therefore, the banks in the two markets sell (buy) funds to (from) banks to which they have lines of credit up to the amount specified by the lines. In October 1981, the Federal Reserve switched the settlement procedure from next-day settlement to same-day settlement for Eurodollar deposits. With the advert of same-day settlement, settlement for both Fed funds and Eurodollar transactions is made at the close of each business day through the Clearing House Interbank Payment System.

III. Data

This paper analyzes hourly Fed funds rates[1] in addition to the effective Fed funds rate and the overnight Eurodollar rate.[2] The effective Fed funds rate is a weighted average rate 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 Eurodollar rate used is the overnight Eurodollar best bid rate (single best quote) in London between 12:00 noon and 1:00 pm Greenwich Mean Time (GMT), which corresponds to 7:00 am and 8:00 am EST. Hourly Fed funds rates are bid rates reported by the International Monetary Market Division of the Chicago Mercantile Exchange. The Fed funds rates at 10:00 am and 1:00 pm[3] are analyzed for hourly Fed funds rates. The period of the data analyzed runs from March 1, 1984, the first day of the maintenance period, to July 1, 1998 on settlement Wednesday. During this period, the

Federal Reserve employed the contemporary reserve accounting system and the two-week maintenance period.

Panels A, B and C of Figure 2 present the effective Fed funds rate (i_t) and the Fed funds rate at 1:00 pm (i_t^1) and at 10:00 am (i_t^{10}) respectively. Panel D plots the overnight Eurodollar rate (r_t). The four interest rates move very similarly. The biggest changes in the four interest rates occur at the same time, the end of 1985 and the end of 1986. Settlement Wednesdays coincide with the last day of the year on those two dates. Table 1 shows summary statistics for the four interest rates and their changes. The changes of each interest rate have very big skewness and kurtosis because of infrequent big changes. When the three days (December 31, 1985 and December 30 and 31, 1986) are removed from the data, skewness and kurtosis are dramatically decreased. Therefore, the analysis should be compatible with big outliers.

Table 2 gives the test results for the null hypothesis that each interest rate is integrated of order one, I(1), against the alternative hypothesis that it is integrated of order zero, I(0). I employ the augmented Dickey-Fuller t-test (ADF) and three modifications of the Dickey Fuller t-test: (1) the test proposed by Elliott et al. (1996), which I denote DF-GLS, (2) the test developed by Elliot (1999), which is named DF-GLSu and (3) the test introduced by Leybourne (1995), which is called DF_{max}. I adopt $\bar{c} = -10$ chosen by Elliot (1999) for DF-GLS and DF-GLSu. The regression includes a constant but not a trend. The null hypothesis of the unit root is not rejected by four unit root tests. Therefore, the empirical model needs to be suitable for the unit root process.

IV. Model Specification

Lee (2003) finds that reserve regulations, reserve accounting conventions and line limits in the U.S. influence the Fed funds market and the overnight Eurodollar market and the interest rates in the two overnight markets show the similar calendar-day effects but the absolute amounts of the calendar-day effects on the overnight Eurodollar rate are smaller than those on the effective Fed funds rate. However, she could not conclude whether the effects of the Federal Reserve Board regulations, reserve accounting conventions and characteristics of the Fed funds market were the same on the overnight Eurodollar rate as on the Fed funds rate. She uses the effective Fed funds rate for the Fed funds rate and the overnight Eurodollar best bid rate in London between 12:00 noon and 1:00 pm Greenwich Mean Time (GMT), which correspond to 7:00 am and 8:00 am EST[4], for the overnight Eurodollar rate. While the effective Fed funds rate is a weighted average rate of transaction rates over the day, the overnight Eurodollar rate is a point-in-time bid rate before the Fed funds market opens. The Fed funds rate and the overnight Eurodollar rate employed by Lee (2003) have two problems: first, the two interest rates are prices of funds traded at different time and second, the Fed funds rate is a transaction rate and the overnight night Eurodollar rate is a bid rate. Because the Fed funds market and the overnight Eurodollar market have identical features except locations and some participants, as discussed in Section I, the predictable calendar-day differences between the effective Fed funds rate and the overnight Eurodollar bid rate might be driven either by market differences in location or by the above two problems with the used data.

This paper disentangles the two explanations by analyzing the Fed funds bid rate at 10:00 am and at 1:00 pm EST in addition to the effective Fed funds rate and the overnight Eurodollar rate between 7:00 am and 8:00 am EST. Analyzing bid rates both for the Fed funds rate and the overnight Eurodollar rate rules out the possible reason that the systematic calendar-day effect differences are caused by the problem that the effective Fed funds rate bounces between bid and ask rates but the overnight Eurodollar rate is a bid rate. Therefore, the problem caused by the used data is only measuring time differences.[5]

The Fed funds rate at 10:00 am and the Fed funds rate at 1:00 pm are the prices of Fed funds in the same Fed funds market at different times (3 hours difference). The two rates can be different not because they are traded in different markets but because they are traded at different times of the day. On the other hand, the overnight Eurodollar rate in London between12:00 noon and 1:00 pm GMT and the Fed funds rates at 10:00 am EST are the prices of funds in different markets and at different times (between 2 and 3 hours difference[6]). The two overnight money market rates may not be the same because they are the prices of funds in different market and at different times. Therefore, by comparing two relationships: the relationship between the overnight Eurodollar rate and the Fed funds rate at 10:00 am and the relationship between the Fed funds rate at 10:00 am and the Fed funds rate at 1:00 pm., the empirical model can control possible sources of bias and provide a statistical sensible test of whether the effects of Federal reseve requirement regulations, reserve accounting conventions and characteristics of the Fed funds market are the same on the Fed funds rate as on the overnight Euurodollar rate.

The Federal funds rate would follow a martingale within a two-week maintenance period under the following conditions: banks are risk neutral; the reserve requirements are the only reason why banks hold reserves; and there is no friction to participate in the Fed funds market, because reserves held on any day of a maintenance period could be perfect substitutes for the purpose of meeting reserve requirements (Hamilton, 1996). This martingale hypothesis does not apply to the Fed funds rate if day t is the first day of a maintenance period. This is because reserves on the first Thursday of a maintenance period are not very substitutable for reserves of the day before, even though there is a provision allowing banks to substitute some amount of reserves across maintenance periods. The empirical model also allows the Fed funds rate to move away from the martingale process on the day of a maintenance period, U.S. holidays and the last day of a quarter.

The conditional means of the effective Fed funds rates are specified to follow two different processes in accordance with the calendar days in order to take into account the martingale hypothesis. They include the effects of the overnight Eurodollar rate on the effective Fed funds rate because overnight Eurodollars could be a close substitute for the Fed funds. If day t is the first day of a maintenance period or the first day of a quarter, the conditional mean for the effective Fed funds rate is described as follows:

$$\begin{aligned} E(i_t \mid I_{t-1}) = {} & a_{11} i_{t-1} + a_{12} i_{t-2} + \cdots + b_{11}\Delta r_{t-1} + b_{12}\Delta r_{t-2} + \cdots \\ & + c_{11}(r_{t-(1+w)} - i_{t-(1+w)}) + c_{12}(r_{t-(3+w)} - i_{t-(3+w)}) + \cdots + \boldsymbol{h}_{11} + \sum_{j=1}^{8} \boldsymbol{b}_{1j} h_{jt} . \end{aligned} \tag{1}$$

For all other days, it is

$$\begin{aligned} E(i_t \mid I_{t-1}) = {} & e_{11} i_{t-1} + e_{12} i_{t-2} + \cdots + f_{11}\Delta r_{t-1} + f_{12}\Delta r_{t-2} + \cdots \\ & + g_{11}(r_{t-(1+w)} - i_{t-(1+w)}) + g_{12}(r_{t-(3+w)} - i_{t-(3+w)}) + \cdots + \sum_{s=2}^{10} h_{1s} d_{st}\,{}_{1} + \sum_{j=1}^{8} b_{1j} h_{jt} \end{aligned} \tag{2}$$

where w = 0 or 1, i_t is the effective Fed funds rate and r_t is the overnight Eurodollar rate. The information set, I_{t-1}, includes all relevant information available at the end of day $t-1$ to forecast the interest rates on day t. The variables in the information set are lagged Fed funds rates, lagged overnight Eurodollar rates and the date, i.e., $I_{t-1} = \{ t, i_{t-1}, i_{t-2,} \cdots, i^h_{t-1}, i^h_{t-2}, \cdots, r_{t-1}, r_{t-2}, \cdots \}$, where i^h_{t-1} is the Fed fund rate at *h* o'clock on day $t-1$. The reason why the explanatory variables of equations (1) and (2) include only lagged effective Fed funds rates not lagged hourly Fed funds rates is that the effective Fed funds rate is the average rate during the day so it contains all information which the hourly Fed funds rats could have in the Fed Funds market during the day. The independent variables also include lagged overnight Eurodollar rates because the overnight Eurodollar rate is the price of the funds substitutable with the Fed funds. The variable d_{st} for $s = 2, 3, \cdots, 10$ is a dummy variable that equals 1 if day t is the sth day of a reserve maintenance period. For example, $d_{2t} = 1$ if day t is the second day of a maintenance period (first Friday), and $d_{2t} = 0$ otherwise. The variable d_{10t} takes the value 1 for the last day of a maintenance period (settlement Wednesday), and equals 0 otherwise. The variable h_{jt} for $j = 1, 2, \cdots, 8$ is also a dummy variable to denote U.S. holidays and the last day of a quarter or a year. 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} to h_{8t} denote the last day of a quarter. The definitions of d_{st} and h_{jt} are denoted in Tables 3 and 4.

The regression equations (1) and (2) take into account that the hypothesis of the unit root is failed to reject. The usual *t* or F test associated with any hypotheses about linear combinations of the coefficients a_i's in the following specification:

$$i_t = a_1 i_{t-1} + a_2 i_{t-2} + \cdots + a_p i_{t-p} + e_t$$

except the sum $a_1 + a_2 + \cdots + a_p$ (Hamilton, pp. 516-527). Because the error term is stationary, stationary regressors can be included in the above regression. The explanatory variables can incorporate the lagged changes in the overnight Eurodollar rates ($\Delta r_{t-1}, \Delta r_{t-2}, \cdots$), the lagged differentials between the overnight Eurodollar rate and the effective Fed funds rate ($r_{t-1} - i_{t-1}, r_{t-2} - i_{t-2}, \cdots$) and dummy variables in addition to the lagged effective Fed funds rates ($i_{t-1}, i_{t-2}, \cdots$). However, if the independent variables include three kinds of lagged variables, they are linearly dependent[7]. To prevent this multicolinearity problem, the explanatory variables have to contain only odd lags (w = 1) or even lags (w = 0) of differences between the overnight Eurodollar rate and the Fed funds rate. The independent variables have the lagged levels of the effective Fed funds rate instead of its changes in order not to place restrictions on the coefficients of the lagged Fed funds rates. The number of lags for all series is chosen by the Bayesian Schwartz Information Criteria and the F test is taken to decide the lags for each series.

For the same reason, the conditional means of the Fed funds rate at 10:00 am and at 1:00 pm are estimated by two separate equations. To forecast the Fed funds rate at 1:00 pm, possible explanatory variables are lagged Fed funds rates at 1:00 pm, lagged effective Fed fund rates, lagged overnight Eurodollar rates, and their differences. Because of the multicolinearity problem and nonstationarity, on the first day of a maintenance period or the first day of a quarter, the conditional mean of the Fed funds rate at 1:00 pm is specified as

$$
\begin{aligned}
E(i_t^1 \mid I_{t-1}) = {} & a_{21} i_{t-1}^1 + a_{22} i_{t-2}^1 + \cdots + b_{21} \Delta i_{t-1} + b_{22} \Delta i_{t-2} + \cdots + c_{21} \Delta r_{t-1} + c_{22} \Delta r_{t-2} + \cdots \\
& + e_{21} (i_{t-(1+w)}^1 - i_{t-(1+w)}) + e_{22} (i_{t-(3+w)}^1 - i_{t-(3+w)}) + \cdots + f_{21} (i_{t-(1+v)}^1 - r_{t-(1+v)}) \\
& + f_{22} (i_{t-(3+v)}^1 - r_{t-(3+v)}) + \cdots + \boldsymbol{h}_{21} + \sum_{j=1}^{8} \boldsymbol{b}_{2j} h_{jt} .
\end{aligned} \tag{3}
$$

On other days, it is

$$
\begin{aligned}
E(i_t^1 \mid I_{t-1}) = {} & g_{21} i_{t-1}^1 + g_{22} i_{t-2}^1 + \cdots + k_{21} \Delta i_{t-1} + k_{22} \Delta i_{t-2} + \cdots + l_{21} \Delta r_{t-1} + l_{22} \Delta r_{t-2} + \cdots \\
& + m_{21} (i_{t-(1+w)}^1 - i_{t-(1+w)}) + m_{22} (i_{t-(3+w)}^1 - i_{t-(3+w)}) + \cdots + n_{21} (i_{t-(1+v)}^1 - r_{t-(1+v)}) \\
& + n_{22} (i_{t-(3+v)}^1 - r_{t-(3+v)}) + \cdots + \sum_{s=2}^{10} \boldsymbol{h}_{2s} d_{st} + \sum_{j=1}^{8} \boldsymbol{b}_{2j} h_{jt}
\end{aligned} \tag{4}
$$

where w= 0 or 1, v = 0 or 1, i_t^1 indicates the Fed funds rate at 1:00 pm and the definitions of the dummy variables d_{st} and h_{jt} are the same as those given in equations (1) and (2). To capture autoregressive terms, the lagged Fed funds rates at 1:00 pm are included in the explanatory variables in addition to the lagged effective Fed funds rates and the lagged overnight Eurodollar rates. The conditional means of the Fed funds rate at 10:00 am (i_t^{10}) are specified the same as equations (3) and (4) with i_t^{10} instead of i_t^1.

As Lee (2003) shows, the overnight Eurodollar rate is affected by the lagged Fed funds rate. Therefore, the conditional mean for the overnight Eurodollar rate is estimated by two separate equations because the conditional mean of the Fed funds rate has different specifications depending on which day of a maintenance period day t corresponds to and whether day t is the first day of a quarter. For the same reason as equations (1) through to (4), if day t is the first day of a maintenance period or the first day of a quarter, the conditional mean of the overnight Eurodollar rate is

$$E(r_t \mid I_{t-1}) = a_{41}r_{t-1} + a_{42}r_{t-2} + \cdots + b_{41}\Delta i_{t-1} + b_{42}\Delta i_{t-2} + \cdots \\ + c_{41}(r_{t-(1+w)} - i_{t-(1+w)}) + c_{42}(r_{t-(3+w)} - i_{t-(3+w)}) + \cdots + \eta_{41} + \sum_{j=1}^{8} \beta_{4j} h_{jt}. \tag{5}$$

On all other days, it is

$$E(r_t \mid I_{t-1}) = e_{41}r_{t-1} + e_{42}r_{t-2} + \cdots + f_{41}\Delta i_{t-1} + f_{42}\Delta i_{t-2} + \cdots \\ + g_{41}(r_{t-(1+w)} - i_{t-(1+w)}) + g_{42}(r_{t-(3+w)} - i_{t-(3+w)}) + \cdots + \sum_{s=2}^{10} h_{4s} d_{st} + \sum_{j=1}^{8} b_{4j} h_{jt}. \tag{6}$$

Because Sprindt and Hoffmeister (1988), Griffiths and Winters (1995), Hamilton (1996), Cyree and Winters (2001*a* and *b*), Lee (2003) and Bartolini, Bertola and Prati (2002) show that the Fed funds rate exhibits heteroskedasticity, the error terms are specified as the Exponential GARCH (EGARCH) process. The empirical model for the four interest rates is

$$y_{kt} = E(y_{kt} \mid I_{t-1}) + \sigma_{kt} v_{kt}, \tag{7}$$

where y_{kt} is the effective Fed funds rate (i_t), the Fed funds rate at 1:00 pm (i_t^1), the Fed funds rate at 10:00 am (i_t^{10}) and the overnight Eurodollar rate (r_t) for $k = 1, 2, 3, 4$ respectively. The innovation v_{kt} is a zero-mean i.i.d. random variable and σ_{kt} is a function of date t and lagged interest rates. As in Hamilton (1996) and Lee (2003), v_{kt} is presumed to follow a mixture of normal distributions[8] to capture uncommon large changes. The innovation v_{kt} is drawn from a $N(0,1)$ with probability p_k and from a $N(0, \tau_k^2)$ distribution, which has a variance different from 1 with probability $(1 - p_k)$. The density of the mixture distribution is

$$g(v_{kt}; \theta_k) = \frac{p_k}{\sqrt{2\pi}} \exp\left(\frac{-v_{kt}^2}{2}\right) + \frac{1 - p_k}{\tau_k \sqrt{2\pi}} \exp\left(\frac{-v_{kt}^2}{2\tau_k^2}\right), \tag{8}$$

where θ_k is a vector of population parameters that includes p_k and τ_k^2. The conditional variance of this distribution is given by

$$E\{[y_{kt} - E(y_{kt} \mid I_{t-1})]^2 \mid I_{t-1}\} = \sigma_k^2 [p_k + (1-p_k)\tau_k^2]\,. \tag{9}$$

The log of the conditional variance follows Hamilton's (1996) modification of Nelson's (1991) exponential GARCH model. It is assumed that the GARCH effects are integrated. 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 the 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 σ_{kt}^2 evolves according to

$$\begin{aligned} \ln(\sigma_{kt}^2) - \sum_{s=1}^{10} \xi_{ks} d_{st} - \sum_{j=1}^{8} \kappa_{kj} h_{jt} = {} & \delta_k \left[\ln(\sigma_{kt-1}^2) - \sum_{s=1}^{10} \xi_{ks} d_{st-1} - \sum_{j=1}^{8} \kappa_{kj} h_{jt-1} \right] \\ & + (1-\delta_k) \frac{1}{10} \sum_{m=b_t}^{l_t} \left[\ln(\sigma_{km}^2) - \sum_{s=1}^{10} \xi_{ks} d_{sm} - \sum_{j=1}^{8} \kappa_{kj} h_{jm} \right] \\ & + \alpha_k \left[q(v_{kt-1}) - Eq(v_{kt-1}) + \aleph_k v_{kt-1} \right], \end{aligned} \tag{10}$$

where b_t and l_t are the beginning and the ending days of the previous maintenance period respectively. The unconditional expectation of $\ln \sigma_{kt}^2$ equals $\sum_{s=1}^{10} \xi_{ks} d_{st} + \sum_{j=1}^{8} \kappa_{kj} h_{jt}$.

Hamilton's (1996) hypothesis is adopted and ξ_{ks} has the same value for day 2 to day 7:

$$\xi_{k2} = \xi_{k3} = \cdots = \xi_{k7}\,. \tag{11}$$

A positive value of $(\alpha_k \cdot \aleph_k)$ indicates that volatility in conditional variance tends to rise when innovation of y_{kt-1} is positive. Because the nondifferentiability of the likelihood function makes it impossible to maximize the likelihood function numerically at v_{kt-1} = 0, the function $q(v_{kt-1})$ takes the following form, as Hamilton (1997) suggested:

$$q(v_{kt-1}) = \begin{cases} (1+v_{kt-1}^2)/2 & for|\, v_{kt-1}\,| < 1 \\ |\, v_{kt-1}\,| & for\,|\, v_{kt-1}\,| \geq 1\,. \end{cases} \tag{12}$$

This function is differentiable everywhere including $v_{kt-1} = 0$. The expected value of $q(v_{kt-1})$ is calculated by numerically integrating $q(v_{kt-1})$ with its density in the equation (8) with respect to v_{kt-1}.

Since

$$y_{kt} = E(y_{kt} \mid I_{t-1}) + s_{kt} v_{kt} = f(v_{kt})\,, \tag{13}$$

the conditional density of y_{kt} would be

$$f\,(y_{kt} \mid I_{t-1}) = g(v_{kt})\left|\frac{dv_{kt}}{dy_{kt}}\right| \tag{14}$$

where

$$v_{kt} = f^{-1}(y_{kt}) = \left[y_{kt} - E(y_{kt} \mid I_{t-1})\right] / s_{kt} \tag{11}$$

and $E(y_{kt} \mid I_{t-1})$ is specified in (1) through (6). Hence the log of the density is

$$\ln\, f\,(y_{kt} \mid I_{t-1}) = \ln\left[g(v_{kt})\right] - \ln(s_k^2)/2\,. \tag{12}$$

The EGARCH model is estimated by maximizing the conditional log likelihood with respect to the population parameters subject to two constraints, $0 \leq p_k \leq 1$ and $t_k^2 > 0$.

V. Empirical Results

This section presents the empirical results of the conditional mean parameters and the conditional variance parameters of equation (7) for the effective Fed funds rate, the

Fed funds rate at 1:00 pm, the Fed funds rate at 10:00 am and the overnight Eurodollar rate in Tables 3 to 8. The conditional means of the four overnight rates clearly follow different processes depending on whether the day is the first day of a maintenance period or the first day of a quarter as equations (1.1) through to (4.2) in Table 3. For all four interest rates, the sums of the coefficients of their own lags are very close to one as expected based on the unit root test. The coefficients of their own first lags of the conditional means are very close to one on typical days other than the first day of a maintenance period or the first day of a quarter. However, they are much smaller than one on the first day of a maintenance period or on the first day of a quarter. The coefficients of the lags beyond one are much smaller than those of the first lags. The lagged overnight Eurodollar rates have significant effects on the conditional mean of the effective Fed funds rate if day *t* is the first day of a maintenance period or the first day of a quarter but they are not significant on other days. The results justify that the conditional mean of each interest rate needs different specifications depending on the day of a maintenance period and the day of a quarter.

Yesterday's difference between the point-in-time interest rate (the Fed funds rate at 1:00 pm, the Fed funds rate at 10:00 am or the overnight Eurodollar rate) and the effective Fed funds rate has important effects on the change in the point-in-time interest rate today. The coefficients of $(i_{t-1}^{10} - i_{t-1})$ and $(i_{t-1}^{1} - i_{t-1})$ of equations (2.1) through to (3.2) in Table 3 are close to -0.6 but the coefficients of $(r_{t-1} - i_{t-1})$ of equations (4.1) and (4.2) are -0.19 and -0.35[9] respectively, which are much smaller than -0.6 in absolute value. When yesterday's Fed funds rate at 10:00 am (1:00 pm) is 10 basis points higher than yesterday's effective Fed funds rate, it reduces the Fed funds rate at 10:00 am (1:00 pm) by about 6 basis points today. When yesterday's overnight Eurodollar rate between 7:00 am and 8:00 am EST is 10 basis points higher than the effective Fed funds rate, the overnight Eurodollar rate decreases by about 3.5 basis points today. The adjustment speed of yesterday's deviation of the Fed funds rates at 1:00 pm and 10 am from the effective Fed funds rate is the same, but larger than that of the overnight Eurodollar rate from the effective Fed funds rate. This result implies that the overnight Eurodollar rate is influenced by yesterday's Fed funds rate but the overnight Eurodollar rate is not tied with the Fed funds rate as much as the point-in-time Fed funds rates are fastened between them.

Tables 4 and 5 show the effects of the calendar-day dummies on the conditional means of the four interest rates. Previous research (Campbell (1987), Saunders and Urich (1988), Spindt and Hoffmeister (1988), Griffiths and Winters (1995), Hamilton (1996) and Bartolini, Bertola and Prati (2002)) documents that the Federal Reserve regulations and the reserve accounting system create the predictable calendar-day effects on the conditional means and the conditional variances of the Fed funds rate. The Fed funds rate tends to fall during the reserve maintenance period. It decreases on Fridays and before holidays (before non-trading days) and second Tuesdays (before settlement Wednesdays). It increases on Mondays, after holidays (after non-trading days) and settlement Wednesdays. Its variances increase as settlement Wednesday approaches and are greatest on settlement Wednesdays. Lee (2003) argues that the overnight Eurodollar rate has a similar pattern of calendar-day effects as the Fed funds rate but with smaller absolute values. Griffiths and Winters (1997*b*) believe that the Friday and Monday effects on the Fed funds rate are generated not only by the Federal Reserve regulations but also by the incentives of participants to avoid idle cash over non-trading weekends. However, Kamath, et al. (1995) do not find negative weekend effects on one-month, two-month and three-month Eurocurrency rates in London for the Eurodollar, Euro Canadian dollar, Euro Pound Sterling, and Euro Swiss Franc. Based on their research, I consider negative weekend effects caused by the incentive of a U.S. bank which does not know whether it needs the full credit of a weekend loan and does not want to hold unwanted excess reserves by the Federal Reserve regulations. Ogden (1987), Allan and Saunders (1992), Griffiths and Winters (1997*a*) and Musto (1997) find changes in interest rates in money markets as the last day of a quarter approaches, known as the turn-of-the-quarter effect. The explanatory variables for the overnight interest rates include the dummy variables for the last day of a quarter but their effects are not considered as effects initiated by the Federal Reserve regulations. Therefore, the effects of the last day of a quarter are not discussed in this paper.

The effects of all 14 calendar-day dummy variables on the conditional mean of the Fed funds rate at 1:00 pm have the same signs as those of the effective Fed funds rate. The effective Fed funds rate and the Fed funds rate at 1:00 pm tend to have almost same calendar-day effects. It is quite surprising because 1:00 pm is 5 and half hours ahead of the closing time of the Fed funds market while Griffiths and Winters (1995) report that only the afternoon Fed funds rate shows the key behavioral features of the Fed funds rate. The effects of the 12 out of 14 dummy variables on the conditional mean of the Fed funds rate at 10:00 am have the same significant or non-significant signs as the effective Fed funds rate. On the other hand, 8 calendar-day effects on the conditional mean of the overnight Eurodollar rate have the same significant or non-significant signs as the effective Fed funds rate. But the effects of 10 calendar-day dummy variables on the overnight Eurodollar rate have the same significant or non-significant signs as the effective Fed funds rate in Lee (2003).[10] From these results, it is hard to conclude whether the calendar-day effect differences in Lee (2003) are caused by market differences or by time differences in collecting interest rates.

Even though the two coefficients of the Fed funds rate at 10:00 am ($\boldsymbol{h}_{35}$ and $\boldsymbol{h}_{39}$) are not significant unlike those of the Fed funds rate at 1:00 pm, the coefficients of the other calendar-day dummy variables of the Fed funds rate at 10:00 am are almost the same as those of the Fed funds rate at 1:00 pm except for the coefficient on the first Tuesday, $\boldsymbol{h}_{34}$. The values of $\boldsymbol{b}_{32}$ (the coefficient of the dummy variable to indicate that the day precedes a three-day holiday) and $\boldsymbol{b}_{33}$ (the coefficient of the dummy variable to exhibit that the day follows a one-day holiday) for the Fed funds rate at 10:00 am are much smaller than those coefficients of the conditional mean of the Fed funds rate at 1:00 pm. With those values, the holiday effects on the Fed funds rate in the early afternoon and in the morning look different. The coefficients of these two dummy variables are different using the Fed funds rate at 2:00 pm. Although 2:00 pm is 1 hour later than 1:00 pm, the coefficients of the two dummy variables, d_{2t} and d_{3t}, for the conditional mean of the Fed funds rate at 2:00 pm are smaller than those for the Fed funds rate at 1:00 pm. The two values are -0.031 and 0.071, almost the same as the coefficients for the effective Fed funds rate, and very similar to the coefficients for the Fed fund rate at 10:00 am ($\boldsymbol{b}_{32}$ and $\boldsymbol{b}_{33}$). These results support the hypothesis that the effects of the two holiday dummies (d_{2t} and d_{3t}) on the Fed funds rate are not different between 10:00 am and 1:00 pm.

The effects of the calendar-day dummies on the conditional mean of the Fed funds rate at 10:00 am are 1 basis point or 15 % different from those on the Fed funds rate at 1:00 pm except for three coefficients, h_{34}, h_{35} and h_{39}.

Table 6 summarises the relationship of the calendar-day effects on the conditional means of the Fed funds rates at 1:00 pm and 10:00 am, and the overnight Eurodollar rate. The calendar-day effects are categorized into four groups. The first group includes first and second Fridays. The calendar-day dummy variables in this group have the same effects on the Fed funds rate in the morning and in the early afternoon and the overnight Eurodollar rate. There are no Friday effect differences in the Fed funds market and the overnight Eurodollar market. The second group consists of seven calendar-day dummy variables: first Monday, second Thursday, second Monday, second Wednesday, the day preceding a three-day holiday, the day after a one-day holiday and the day after a three-day holiday. They have the same effects on the Fed funds rate at 1:00 pm and at 10:00 am but smaller effects on the overnight Eurodollar rate. The settlement Wednesday effect on the Fed funds rate at 10:00 am is different from the result of Griffiths and Winters (1995), who find that the morning Fed funds rate does not rise on settlement Wednesdays but the afternoon Fed funds rate rises significantly. The seven calendar-day dummy variables in this group defend the hypothesis that the calendar-day effect differences between the effective Fed funds rate and the overnight Eurodollar rate are produced by the two market differences. The first Tuesday belongs to the third group. The first Tuesday has the largest effect on the Fed funds rate at 1:00 pm and the second largest effect on the Fed funds rate at 10:00 am in absolute value. It is not significant on the overnight Eurodollar rate. The first Wednesday and the second Tuesday are in the fourth group. The effects of those two days on the conditional mean of the Fed funds rate at 1:00 am are negative but the effects are not significant on the conditional means of the Fed funds rate at 10:00 am and the overnight Eurodollar rate. The variables in the fourth group could be in the third group because the effects of first Wednesday and second Tuesday might be weaker on the overnight Eurodollar rate than on the Fed funds rate at 10:00 am like the third group but they are not significant for both rates. Therefore, the three calendar-days in the third and the fourth groups support the hypothesis that the calendar-day effect differences can be due either to market differences or to time difference in collecting the two interest rates.

Seven calendar-day effects in the second group attribute the causes of the calendar-day effect differences between the effective Fed funds rate and the overnight Eurodollar rate to financial market differences while three calendar-day effects ascribe them either to different market characteristics or to trading time difference. The time difference between the Fed funds rates at 1:00 pm and at 10:00 am is 3 hours and the time gap between the Fed funds rate at 10:00 am and the overnight Eurodollar rate in London between 7:00 am and 8:00 am EST is between 2 and 3 hours. The calendar-day effects on the Fed funds rates at 10:00 am tend to have the same pattern as those on the Fed funds rate at 1:00 pm but there are some discrepancies between the two which might be produced by transaction time difference. On the other hand, even if the transaction time difference between the Fed funds rate at 10:00 am and the overnight Eurodollar rate is almost the same as (or possibly less than) the time gap between the Fed funds rates at 10:00 am and at 1:00 pm, the overnight Eurodollar rate in London does not show the similar calendar effects to the Fed funds rate at 10:00 am as the Fed funds rate at 10:00

am does to the Fed funds rate at 1:00 pm. The dissimilarity between the overnight Eurodollar rate between 7:00 am and 8:00 am EST and the Fed funds rate at 10:00 am is larger than the amounts which could be explained by the transaction time difference. Hence, the results of the calendar-day effects on the three conditional means confirm that the predictable calendar-day effect differences are caused mainly by market differences.

The effects of the day of a maintenance period on the conditional variance of the four interest rates are reported in Table 7. The effects have somewhat different patterns between the four interest rates. On first Thursdays, the variances of the effective Fed funds rate and the overnight Eurodollar rate are higher than a usual day but the variances of the Fed funds rates at 1:00 pm and 10:00 am are almost the same or a little lower than a usual day.[11] The variances of the four interest rates are higher on the last three days of a maintenance period than a usual day. The conditional variances of the three Fed funds rates tend to increase over the last three days of a maintenance period $(x_{k2} < x_{k8} < x_{k9} < x_{k10}$ for $k = 1, 2, 3)$ but the conditional variance of the overnight Eurodollar rate increases during the last two days of a maintenance period $(x_{42} < x_{48} \approx x_{49} < x_{4,10})$. The conditional variances of the four interest rates are highest on settlement Wednesday. The results of the conditional variances do not support one reason against another.

The estimates for the other parameters are shown in Table 8. The innovations (n_{kt}) of the four interest rates are drawn from a mixture of two normal distributions, a $N(0,1)$ and a $N(0, t_k^2)$ for $k = 1, 2, 3, 4$. The variance t_4^2 of the overnight Eurodollar rate is bigger than the variances of the other Fed funds rates. This means that the variance of infrequent large changes of the overnight Eurodollar rate is larger. The other parameters for the conditional variances are very similar between the four interest rates. The estimation results of a mixture of normal distributions provide the support of the claim that the overnight Eurodollar rate moves differently from the Fed funds rate because of market differences between the Fed funds market and the overnight Eurodollar market even if the overnight Eurodollar rate is affected by the Fed funds rate.

VI. Conclusion

By using the Fed funds bid rates at 10:00 am and 1:00 pm, the empirical model for cross-market interest rates restrains the problem of bias and provides a sensible methodology to test the hypothesis: the effects of the Federal Reserve Board regulations, reserve accounting conventions and characteristics of the Fed funds market are the same on the overnight Eurodollar rate as on the Fed funds rate. This paper finds that those effects are smaller on the overnight Eurodollar rate than on the Fed funds rate. The calendar-day effects on the overnight Eurodollar rate are caused by Federal Reserve regulations but the effects are smaller than those on the Fed funds rate. Even if the Fed funds rate and the overnight Eurodollar rate are collected at the same time, the overnight Eurodollar rate would show systematic smaller calendar-day effects than the Fed funds rate.

The result implies that the overnight Eurodollar rate is not perfectly integrated with the Fed funds rate. This is because of the bid-ask spread and market frictions, such as line limits of credit and transaction cost in the two money markets.

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Figure 1
Contemporary Reserve Accounting System (February 1984 - July 1998)

Two-week reserve computation period for transaction deposits											
Day 9	Day 10	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**	**Day 10**
Tue	Wed	**Thur**	**Fri**	**Mon**	**Tue**	**Wed**	**Thur**	**Fri**	**Mon**	**Tue**	**Wed**
		Two-week Reserve maintenance period									

Figure 2
The effective Fed funds rate, the Fed funds rate at 1:00 pm, the Fed funds rate at 10:00 am and the overnight Eurodollar rate

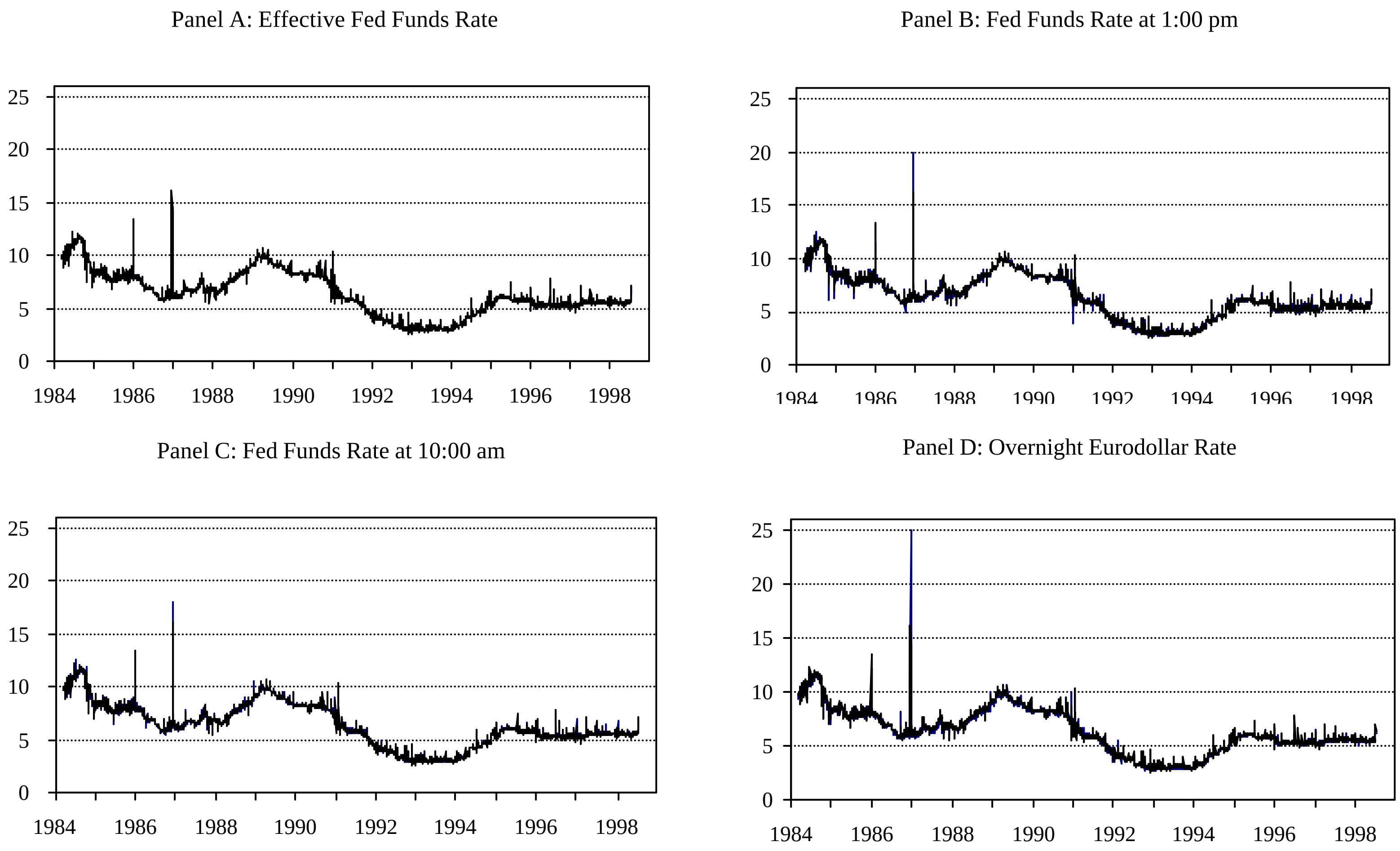

Table 1
Summary Statistics for the Fed Funds Rates and the overnight Eurodollar Rate and their Differentials from 1984:03 to 1998:06

	Mean	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis
i_t	6.364	16.170	2.580	2.066	0.305	2.763
i_t^1	6.339	20.000	2.625	2.061	0.373	3.215
i_t^{10}	6.343	18.000	2.813	2.053	0.339	2.938
r_t	6.283	25.000	2.750	2.056	0.446	4.455
Δi_t	-0.001	7.790	-7.890	0.374	0.185	130.853
		2.830^+	-2.700^+	0.303^+	0.781^+	19.148^+
Δi_t^1	-0.001	7.750	-13.625	0.399	-8.839	438.356
		3.125^+	-3.750^+	0.280^+	-0.172^+	33.982^+
Δi_t^{10}	-0.001	7.250	-11.750	0.326	-9.771	550.439
		1.625^+	-2.000^+	0.218^+	0.144^+	13.681^+
Δr_t	-0001	13.500	-17.125	0.433	-8.549	970.818
		2.250^+	-2.500^+	0.196^+	-0.714^+	29.182^+

Note: All numbers are percentage rates for (1) the effective Fed funds rate (i_t) and its differential (Δi_t), (2) the Fed funds bid rate at 1:00 pm (i_t^1) and its differential (Δi_t^1), (3) the Fed funds bid rate at 10:00 am (i_t^{10}) and its differential (Δi_t^{10}), and (4) the overnight Eurodollar bid rate in London (r_t) and its differential (Δr_t). The sample period is from March 1, 1984 to July 1, 1998. + indicates the statistics of the series leaving out three observations, December 31, 1985 and December 30 and 31, 1986.

Table 2
Unit Root Test

	ADF	DF-GLS	DF-GLSu	DF_{max}
i_t	-1.790	-0.117	-1.635	-0.371
i_t^{10}	-1.787	-0.106	-1.635	-0.344
i_t^{1}	-1.808	-0.124	-1.662	-0.416
r_t	-1.855	-0.271	-1.726	-0.556
critical value (5%), $T=\infty$	-2.86	-2.86	-2.73	-2.43

Table 3
Maximum Likelihood Estimates of the Conditional Mean

(1) The effective Fed funds rate

(1.1) Day t is the first day of a maintenance period or the first day of a quarter

$$E(i \mid I_{t-1}) = \underset{(0.057)}{0.568 i_{t-1}} + \underset{(0.051)}{0.043 i_{t-2}} + \underset{(0.030)}{0.071 i_{t-3}} + \underset{(0.045)}{0.325 i_{t-4}} - \underset{(0.057)}{0.410 \Delta r_{t-1}} - \underset{(0.051)}{0.156 \Delta r_{t-2}} - \underset{(0.054)}{0.417 (i_{t-1} - r_{t-1})}$$
$$+ \boldsymbol{h}_{11} + \sum_{j=1}^{8} \boldsymbol{b}_{1j} h_{jt}.$$

(1.2) For all other days

$$E(i \mid I_{t-1}) = \underset{(0.013)}{1.055 i_{t-1}} - \underset{(0.011)}{0.088 i_{t-2}} + \underset{(0.009)}{0.015 i_{t-3}} + \underset{(0.007)}{0.016 i_{t-4}} + \sum_{S=2}^{10} \boldsymbol{h}_{1s} d_{st} + \sum_{j=1}^{8} \boldsymbol{b}_{1j} h_{jt}.$$

(2) The Fed funds rate at 1:00 pm

(2.1) Day t is the first day of a maintenance period or the first day of a quarter

$$E(i_t^1 \mid I_{t-1}) = \underset{(0.072)}{0.706 i_{t-1}^1} + \underset{(0.058)}{0.145 i_{t-2}^1} + \underset{(0.062)}{0.147 i_{t-3}^1} - \underset{(0.071)}{0.490 \Delta i_{t-1}} - \underset{(0.069)}{0.481 \Delta i_{t-2}} - \underset{(0.044)}{0.423 \Delta i_{t-3}} - \underset{(0.068)}{0.605 (i_{t-1}^1 - i_{t-1})}$$
$$+ \boldsymbol{h}_{21} + \sum_{j=1}^{8} \boldsymbol{b}_{2j} h_{jt}.$$

(2.2) For all other days

$$E(i_t^1 \mid I_{t-1}) = \underset{(0.001)}{0.996 i_{t-1}^1} + \underset{(0.012)}{0.079 \Delta i_{t-1}} - \underset{(0.033)}{0.608 (i_{t-1}^1 - i_{t-1})} + \sum_{S=2}^{10} \boldsymbol{h}_{2s} d_{st} + \sum_{j=1}^{8} \boldsymbol{b}_{2j} h_{jt}.$$

(3) The Fed funds rate at 10:00 am

(3.1) Day t is the first day of a maintenance period or the first day of a quarter

$$E(i_t^{10} \mid I_{t-1}) = \underset{(0.049)}{0.663 i_{t-1}^{10}} + \underset{(0.050)}{0.182 i_{t-2}^{10}} + \underset{(0.043)}{0.152 i_{t-3}^{10}} - \underset{(0.049)}{0.452 \Delta i_{t-1}} - \underset{(0.042)}{0.429 \Delta i_{t-2}} - \underset{(0.035)}{0.355 \Delta i_{t-3}} - \underset{(0.050)}{0.537 (i_{t-1}^{10} - i_{t-1})}$$
$$+ \boldsymbol{h}_{31} + \sum_{j=1}^{8} \boldsymbol{b}_{3j} h_{jt}$$

(3.2) For all other days

$$E(i_t^{10} \mid I_{t-1}) = \underset{(0.016)}{1.029 i_{t-1}^{10}} - \underset{(0.016)}{0.033 i_{t-2}^{10}} - \underset{(0.026)}{0.627 (i_{t-1}^{10} - i_{t-1})} + \underset{(0.010)}{0.103 (i_{t-2}^{10} - i_{t-2})} + \sum_{S=2}^{10} \boldsymbol{h}_{3s} d_{st} + \sum_{j=1}^{8} \boldsymbol{b}_{3j} h_{jt}$$

(4) The overnight Eurodollar rate

(4.1) Day t is the first day of a maintenance period or the first day of a quarter

$$E(r_t \mid I_{t-1}) = \underset{(0.048)}{0.359 r_{t-1}} + \underset{(0.077)}{0.326 r_{t-2}} + \underset{(0.054)}{0.316 r_{t-3}} - \underset{(0.040)}{0.133 \Delta i_{t-1}} - \underset{(0.043)}{0.185 (r_{t-1} - i_{t-1})} + \boldsymbol{h}_{41} + \sum_{j=1}^{8} \boldsymbol{b}_{4j} h_{jt}$$

(4.2) For all other days

$$E(r_t \mid I_{t-1}) = \underset{(0.024)}{0.950 r_{t-1}} + \underset{(0.025)}{0.045 r_{t-2}} + \underset{(0.016)}{0.047 \Delta i_{t-1}} - \underset{(0.010)}{0.351 (r_{t-1} - i_{t-1})} + \sum_{S=2}^{10} \boldsymbol{h}_{4s} d_{st} + \sum_{j=1}^{8} \boldsymbol{b}_{4j} h_{jt}$$

Table 4
Maximum Likelihood Estimates of the Conditional Mean
(day of the reserve maintenance period effects)

	$E(i_t \mid I_{t-1})$	$E(i_t^1 \mid I_{t-1})$	$E(i_t^{10} \mid I_{t-1})$	$E(r_t \mid I_{t-1})$
s	η_{1s}	η_{2s}	η_{3s}	η_{4s}
1	0.021	0.021	0.017	-0.040
(first Thursday)	(0.017)	(0.016)	(0.014)	(0.024)
2	-0.046*	-0.040*	-0.037*	-0.035*
(first Friday)	(0.007)	(0.007)	(0.008)	(0.008)
3	0.068*	0.079*	0.080*	0.031*
(first Monday)	(0.007)	(0.008)	(0.008)	(0.008)
4	-0.051*	-0.035*	-0.017*	-0.007 ⊗
(first Tuesday)	(0.007)	(0.007)	(0.009)	(0.008)
5	-0.023*	-0.020*	-0.008	-0.009 ⊗
(first Wednesday)	(0.007)	(0.007)	(0.008)	(0.012)
6	0.022*	0.024*	0.024*	-0.016 ⊗
(second Thursday)	(0.006)	(0.007)	(0.008)	(0.011)
7	-0.034*	-0.021*	-0.014*	-0.022*
(second Friday)	(0.006)	(0.007)	(0.007)	(0.009)
8	0.092*	0.108*	0.103*	0.054*
(second Monday)	(0.008)	(0.008)	(0.008)	(0.007)
9	-0.059*	-0.026*	-0.005	0.005
(second Tuesday)	(0.008)	(0.0008)	(0.010)	(0.006)
10	0.148*	0.126*	0.133*	0.059*
(second Wednesday)	(0.016)	(0.013)	(0.011)	(0.010)

Note: The letter s indicates which day of a two-week reserve maintenance period day t falls on. For example, s is equal to 1 if day t is the first Thursday of a maintenance period and s is equal to 10 if day t is the last day of a maintenance period, which is settlement Wednesday. The values of η_{ks} indicate the effects of the dummy variables for day s of the reserve maintenance period on the conditional mean of the effective Fed funds rate, the Fed funds rate at 1:00 pm, the Fed funds rate at 10:00 am and the overnight Eurodollar rate for $k = 1, 2, 3, 4$ respectively. Standard errors are in parentheses. * denotes statistical significance at the 5 % level. ⊗ indicates that the coefficients of the variables are significant at the 5 % level in Lee(2003) but not in this paper.

Table 5
Maximum Likelihood Estimates of the Conditional Mean
(U.S. holiday and the last day of a quarter effects)

j	$E(i_t \mid I_{t-1})$	$E(i_t^1 \mid I_{t-1})$	$E(i_t^{10} \mid I_{t-1})$	$E(r_t \mid I_{t-1})$
	b_{1j}	b_{2j}	b_{3j}	b_{4j}
1	-0.024	-0.015	-0.014	0.004
	(0.017)	(0.025)	(0.025)	(0.015)
2	-0.029*	-0.040*	-0.029*	-0.016
	(0.008)	(0.010)	(0.009)	(0.008)
3	0.067*	0.126*	0.055*	-0.022
	(0.017)	(0.025)	(0.016)	(0.014)
4	0.217*	0.184*	0.156*	0.075*
	(0.012)	(0.012)	(0.012)	(0.009)
5	0.369*	0.251*	0.284*	0.232
	(0.078)	(0.067)	(0.048)	(0.054)
6	-0.485*	-0.082	0.109	0.020
	(0.200)	(0.239)	(0.341)	(0.112)
7	0.042*	0.040*	0.016	{0}
	(0.020)	(0.015)	(0.016)	
8	-0.042	0.036	0.014	{0}
	(0.045)	(0.035)	(0.121)	

Note: The letter j indicates U.S. holidays and the last day of a quarter; $j=1$ 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 the 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 the last day of the 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. The values of b_{kj} indicate the effects of the dummy variables h_{jt} on the conditional mean of the effective Fed funds rate, the Fed funds rate at 1:00 pm, the Fed funds rate at 10:00 am and the overnight Eurodollar rate for $k=1, 2, 3, 4$ respectively. Standard errors are in parentheses. * denotes statistical significance at the 5 % level. {.} indicates the restricted value.

Table 6
The Comparison of the Calendar-Day Effects on the Conditional Means
(day of a maintenance period and U.S. holiday effects)

Group	Maximum Likelihood Estimates	Calendar-day Dummy Variables
I	$\boldsymbol{h}_{2s} \approx \boldsymbol{h}_{3s} \approx \boldsymbol{h}_{4s}$ or $\boldsymbol{b}_{2j} \approx \boldsymbol{b}_{3j} \approx \boldsymbol{b}_{4j}$	first Friday second Friday
II	$\lvert \boldsymbol{h}_{2s} \approx \boldsymbol{h}_{3s} \rvert > \lvert \boldsymbol{h}_{4s} \rvert$ or $\lvert \boldsymbol{b}_{2j} \approx \boldsymbol{b}_{3j} \rvert > \lvert \boldsymbol{b}_{4j} \rvert$	first Monday second Thursday second Monday second Wednesday h_{2t} h_{3t} h_{4t}
III	$\lvert \boldsymbol{h}_{2s} \rvert > \lvert \boldsymbol{h}_{3s} \rvert > \lvert \boldsymbol{h}_{4s} \rvert$ or $\lvert \boldsymbol{b}_{2j} \rvert > \lvert \boldsymbol{b}_{3j} \rvert > \lvert \boldsymbol{b}_{4j} \rvert$	First Tuesday
IV	$\lvert \boldsymbol{h}_{2s} \rvert > \lvert \boldsymbol{h}_{3s} \approx \boldsymbol{h}_{4s} \rvert$ or $\lvert \boldsymbol{b}_{2j} \rvert > \lvert \boldsymbol{b}_{3j} \approx \boldsymbol{b}_{4j} \rvert$	first Wednesday second Tuesday

Note: The estimates $\boldsymbol{h}_{2s}$ and $\boldsymbol{b}_{2j}$ of the conditional mean of the Fed funds rate at 1:00 pm are the coefficient estimates of the calendar-day dummy variables to indicate the day of a maintenance period and the U.S. holiday. The estimates $\boldsymbol{h}_{3s}$ and $\boldsymbol{b}_{3j}$ are those for the Fed funds rate at 10:00 am. The estimates $\boldsymbol{h}_{4s}$ and $\boldsymbol{b}_{4j}$ are those for the overnight Eurodollar rate between 7:00 am and 8: 00 am. All significant coefficients of the above dummy variables have the same sign.

Table 7
Maximum Likelihood Estimates of the Conditional Variance
(day of the reserve maintenance period effects)

	i_t	i_t^1	i_t^{10}	r_t
s	x_{1s}	x_{2s}	x_{3s}	x_{4s}
1	-4.464*	-3.585*	-4.007*	-3.373*
(first Thursday)	(0.446)	(0.314)	(0.320)	(0.441)
2	-4.636*	-3.614*	-3.920*	-4.006*
(first Friday)	(0.427)	(0.292)	(0.301)	(0.432)
3	{-4.636}	{-3.614}	{-3.920}	{-4.006}
(first Monday)				
4	{-4.636}	{-3.614}	{-3.920}	{-4.006}
(first Tuesday)				
5	{-4.636}	{-3.614}	{-3.920}	{-4.006}
(first Wednesday)				
6	{-4.636}	{-3.614}	{-3.920}	{-4.006}
(second Thursday)				
7	{-4.636}	{-3.614}	{-3.920}	{-4.006}
(second Friday)				
8	-3.905*	-3.225*	-3.601*	-3.625*
(second Monday)	(0.432)	(0.322)	(0.312)	(0.422)
9	-3.612*	-3.153*	-3.458*	-3.637*
(second Tuesday)	(0.445)	(0.311)	(0.314)	(0.431)
10	-2.081*	-1.870*	-2.490*	-2.999*
(second Wednesday)	(0.440)	(0.304)	(0.316)	(0.431)

Note: The values of x_{ks} indicate the effects of the dummy variables for sth day of the reserve maintenance period on the natural log of the conditional variances of the effective Fed funds rate, the Federal funds rate at 1:00 pm, the Fed funds rate at 10:00 am and the overnight Eurodollar rate respectively for $k = 1, 2, 3, 4$. Standard errors are in parentheses. * denotes statistical significance at the 5% level. $\{\cdot\}$ indicates the restricted value.

Table 8
Maximum Likelihood Estimates of other Parameters

Parameters	i_t	i_t^1	i_t^{10}	r_t
	$k=1$	$k=2$	$k=3$	$k=4$
$\boldsymbol{d}_k$	0.457*	0.397*	0.378*	0.444*
	(0.041)	(0.053)	(0.047)	(0.061)
$\boldsymbol{a}_k$	0.477*	0.435*	0.446*	0.331*
	(0.029)	(0.029)	(0.031)	(0.026)
$\aleph_k$	0.210*	0.351*	0.249*	0.156*
	(0.043)	(0.042)	(0.041)	(0.083)
p_k	0.818*	0.859*	0.858*	0.870*
	(0.017)	(0.014)	(0.014)	(0.016)
$\boldsymbol{t}_k^2$	9.522*	9.840*	9.875*	12.541*
	(0.711)	(0.753)	(0.768)	(1.265)

Note: The above parameters are the maximum likelihood estimates of equations (7) and (8) for the effective Fed funds rate, the Fed funds rates at 1:00 pm and 10:00 am and the overnight Eurodollar rate. * denotes statistical significance at the 5% level.

Endnotes

[1] The author would like to thank James Hamilton who provided the hourly Fed funds rates given by Drew Winters.

[2] The effective Fed funds rate was downloaded from the Federal Reserve Board web page (http://www.federalreserve.gov/releases/h15/data/b/fedfund.txt). The daily overnight Eurodollar deposit rate was provided by the Federal Reserve Board.

[3] The hourly Fed funds rates are recorded from 9:00 am to 3:00 am EST and at closing time (6:30 pm EST). Because the Fed funds market opens at 8:30 am EST, the Fed funds rate at 9:00 am EST is half an hour after the open of the Fed funds broker market. The Fed funds rate has the biggest variance at the open and at the close of the market (Cyree and Winters, 2001*a*) so the open and the close rate are not used.

[4] Daylight saving time begins for most of the U.S. at 2:00 am on the first Sunday of April and time reverts to standard time at 2:00 am on the last Sunday of October from 1966. In the U.K. it starts at 1:00 am GMT on the last Sunday in March, and ends on the last Sunday in October from 1981. For one week from the last Sunday of March to Saturday before the first Sunday of April, 12:00 noon and 1:00 pm GMT are 6:00 am and 7:00 am EST respectively.

[5] If this paper uses the overnight Eurodollar rate which is synchronous with the Fed funds rate, this problem is avoidable and it is straightforward to answer whether the Federal Reserve regulations and characteristics in the Fed funds market have the same effects on the Fed funds market and the overnight Eurodollar market. Unfortunately, I could not find the historical overnight Eurodollar rate which had been collected while the Fed funds market was open.

[6] Because of daylight saving time, the time difference between the overnight eurodollar rate between 12:00 noon and 1:00 pm GMT and the Fed funds rate at 10:00 am EST is between 3 and 4 hours for 5 business days, from Monday after the last Sunday of March to Friday before the first Sunday of April.

[7] If so, the independent variables are perfectly correlated because

$$r_{t-1} - r_{t-2} = i_{t-1} - i_{t-2} + (r_{t-1} - i_{t-1}) - (r_{t-2} - i_{t-2}) \ .$$

[8] To capture fat-tailed distribution of which kurtosis is big, Bartolini et al (2002) assume the innovation v_{kt} to be distributed as a t-distribution instead of a mixture of normal distributions.

[9] It could be because the effective Fed funds rate is released at 8:30 am EST before the overnight Eurodollar rate used in the paper is observed.

[10] The coefficients of h_{44} and h_{45} in Lee (2003) are significant and their values are -0.012 and -0.011 respectively.

[11] On first Thursdays, the variance of the effective Fed funds rate is 19% higher and the variance of the overnight Eurodollar rate is 88% higher than a usual day.

$$\exp(x_{11} - x_{12}) = 1.188 \text{ and } \exp(x_{41} - x_{42}) = 1.883 .$$

On the other hand, the variance of the Fed funds rate at 1:00 pm is about 3% larger and the variance of the Fed funds rate at 10:00 am is about 8% lower than a usual day.

$$\exp(x_{21} - x_{22}) = 1.029 \text{ and } \exp(x_{31} - x_{32}) = 0.917 .$$