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RECOVERING MARKET EXPECTATIONS OF FOMC RATE CHANGES WITH OPTIONS ON FEDERAL FUNDS FUTURES

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This paper demonstrates how options on federal funds futures, which began trading in March 2003, can be used to recover the implied probability density function (PDF) for future Federal Open Market Committee (FOMC) interest rate outcomes. The discrete nature of the choices made by the FOMC allows for a very straightforward recovery of the implied PDF using ordinary least squares (OLS) estimation. This simple recovery method stands in contrast to the relatively complicated PDF recovery techniques developed for options written on assets such as equities, foreign exchange, or commodity futures where the underlying prices are most appropriately modeled as being drawn from continuous distributions. The OLS estimation is used to recover PDFs for single FOMC meetings as well as PDFs for joint estimation of multiple FOMC meetings, and allows for the imposition of restrictions on the recovered probabilities, both within and across FOMC meetings. Finally, recovered probabilities are used to assess the impact of data releases and Fed communication on the perceived likelihood of actual policy outcomes.

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Options on CBOT fed funds futures are quite possibly the best means available to express market opinions about what the Fed might or might not do at the upcoming meetings. – Chicago Board of Trade

Meetings of the Federal Open Market Committee (FOMC) have always commanded a great deal of attention. Many analysts use the price of a near-to-expiration federal funds futures contract to recover the probability that a change in the target federal funds rate will be announced at the conclusion of the upcoming FOMC meeting.[i] Of course, this simple method of estimation has severe limitations. In particular, probabilities can only be identified under the assumption that the FOMC will choose between just two target rates.[ii]

It has long been recognized (Breeden and Litzenberger (1978)) that option prices can be used to avoid the restrictive assumption inherent in a futures price to recover the entire risk-neutral probability density function (PDF) for an underlying asset's price.[iii] However, until March 14, 2003, options on federal funds futures were not traded. With the introduction of these options by the Chicago Board of Trade (CBOT), it is now possible to recover the entire PDF for the target federal funds rate ahead of an FOMC meeting. Moreover, the fact that the FOMC always changes the target federal funds rate in 25 basis point increments makes the PDF recovery much more straightforward than in the case of assets such as equities, foreign exchange or commodities with prices that are best modeled as realizations drawn from continuous distributions. The main contribution of this paper is to demonstrate how the recovery of the PDF for the target federal funds rate can be cast in an ordinary least squares (OLS) framework.

With several active contracts in the federal funds futures options market, it is possible to jointly recover the PDF for the target federal funds rate for several points in time. Thus, the options market can be used to estimate the probabilities associated with several possible paths for the target federal funds rate over the next several FOMC meetings. There then arise natural restrictions on the probabilities of target rate outcomes across the paths for these jointly estimated FOMC meetings, restrictions that are easily incorporated in the OLS framework.

Other recent research on FOMC decision making describes the target federal funds rate with a parametric statistical model. For example, Hamilton and Jorda (2002) estimate a model in which the

FOMC decides whether to change the target rate according to an autoregressive conditional duration specification. Once a change "trigger" has been reached, the FOMC makes an ordered-probit decision that determines the change in the target rate, according to 25 basis point increments. Similarly, Hu and Phillips (2004) employ a discrete choice model to estimate not only the magnitude of a target rate change, but also the timing of the change. Robertson and Tallman (2001) use a series of VAR models to forecast the one- and two-month ahead federal funds rate. [iv]

These papers differ from ours in several respects. In contrast to the parametric models, where most of the parameter's underlying the model are unchanging through time, our structure can change daily. All that is required is that the basic premises underlying our estimation hold each day: the federal funds target rate will change only on the meeting date; the changes will be in increments that are divisible by 25 basis points; and the possible changes are spanned by the options market. Further, what is of interest to our paper is the daily density of the target rate changes, whereas much of the preceding literature's focus is on the parameter estimates themselves, and not on the forecast density implied by these estimates.

The paper is organized as follows. The first section describes the federal funds market, how it is influenced by FOMC decisions, and the nature of the federal funds futures and options contracts. The second section explains how option prices can be used in an OLS regression to recover the PDF for the target federal funds rate, both for a single upcoming FOMC meeting and jointly for several upcoming FOMC meetings. This section also shows how restrictions can be imposed on the recovered probabilities. The third section presents recovered probabilities, both for single and joint FOMC estimations. A comparison of probabilities recovered from options prices to probabilities recovered from futures prices is found in the fourth section. The fifth section demonstrates a simple regression technique aimed at understanding how market expectations for future target federal funds rates respond to new information such as data releases and commentary from Federal Reserve officials. The sixth section concludes.

I. Federal Funds and Federal Funds Futures and Options

The federal funds rate is the interest rate paid on overnight loans made between depository institutions. It is commonly viewed as an anchor for all interest rates, especially at shorter maturities. Since the late 1980s, the Federal Reserve has implemented monetary policy by using open market operations to target an intended federal funds rate.[v] Thus, the federal funds rate is not determined by market forces but is effectively administered by the Federal Reserve. Although the federal funds rate may vary day to day in response to uncontrollable market factors, Federal Reserve actions are generally successful in achieving the FOMC's federal funds rate target on average. The deviation of the monthly average fed funds rate from its day-weighted average target level is zero over the past five years, with a standard deviation of 5 basis points. Since 1990, the FOMC has always changed the target federal funds rate in multiples of 25 basis points.

In 1988, federal funds futures began trading on the CBOT. Federal funds futures are interest rate futures contracts that are cash settled based on the average rate during the delivery month. In simple terms one can think of the contract as specifying a predetermined average interest rate for a given month.[vi] Thus, a buyer (or seller) can "lock in" a certain interest rate on a borrowed (or loaned) amount—specified to be $5 million for each contract. In practice the loan is not extended; rather, the difference between the market rate and the futures rate at the time the futures contract was bought or sold is multiplied by the notional $5 million dollar loan and is settled in cash.

Federal funds futures contracts are listed on the CBOT for the current month and for each of the 24 months that follow. The futures price is calculated as 100 minus the average daily federal funds rate for the delivery month. So, for example, the July 2004 contract settlement price on June 15, 2004, of 98.725 implies an average federal funds rate over July 2004 of 1.275 percent. Thus, the June 15, 2004, settlement price for the July 2004 contract means that market participants were factoring in some probability of a rate increase at the June 30, 2004, FOMC meeting from the then-current target rate of 1.00 percent. It should be noted that the correspondence between the average federal funds rate implied by the futures price and the expected target federal funds rate can be complicated by the presence of a risk-premium in the futures market.[vii] Nosal (2001), Chernenko, Schwarz and Wright (2004) and Piazzesi and Swanson (2004) have found this risk premium to be relatively small at the short horizons that will be used in this paper, on the order of three basis points at the one-month horizon and six basis points at the two-month horizon.

The futures price on June 15, 2004, also demonstrates the limitations of using the futures price to recover the probability of a change in the target federal funds rate. The implied futures rate of 1.275 percent is more than 25 basis points above the then-current target rate of 1.00 percent. Therefore, for the June FOMC meeting, market participants saw some chance either a 50 basis point increase, a 25 basis point increase, or no change in the target rate. However, the futures price alone cannot recover the three relevant probabilities associated with these three possible outcomes. Option prices can be used to surmount this limitation.

Figure 1 illustrates that the market response to the introduction of trading in federal funds futures was not immediately overwhelming. However, trading volume, for reasons largely not widely understood, picked up dramatically beginning in 2001. This eventual success led the CBOT to introduce trading in options on federal funds futures in March 2003. Purchase of a federal funds futures call (put) option gives the owner the right to exercise and obtain a long (short) position in federal funds futures. The options are American, allowing for exercise at any point in time. Strike prices are introduced around the previous day's settlement price for the futures contract. Around this price are 21 strike prices at 6.25 basis point intervals, with an additional 10 strike prices outside this band (5 below and 5 above) at 12.50 basis point intervals. At a minimum, options at 31 strike prices will be available, although not all of these options will necessarily be traded or priced.

Since the introduction of options on federal funds futures, trading volume has been uneven, as can be seen in Figure 2. As would be expected, volume increases around times of uncertainty concerning possible changes in the stance of monetary policy. Volume increased noticeably during the late spring of 2003, when market commentary suggested the possibility of further FOMC rate cuts to combat fears of deflation. Trading dropped dramatically after the August 12 FOMC statement indicated that policy accommodation could be maintained (i.e., left unchanged) "for a considerable period." The market remained somewhat inactive until the early spring of 2004, when fears of deflation abated, suggesting that the FOMC would soon be ready to switch to a less accommodative policy.

II. Recovering the Implied PDF with Option Prices

Although fed funds futures options are American options, it is instructive to examine the simpler problem of pricing European options. The unique payoff structure of European options relates their price directly to the risk-neutral PDF from which the price of the underlying asset will be drawn. For example, a call option gives its holder the right to purchase the asset at the strike price. Therefore, the price of the call option is a function of both the probability of the underlying asset price moving above the strike price, and the expectation for the underlying asset price given that it has moved above the strike price. This payoff structure allows the price of the option to be written in terms of the PDF.

The recovery and interpretation of the risk-neutral PDF for the target federal funds rate is slightly complicated by three factors. First, the early exercise premium associated with American options invalidates the relatively straightforward relationship between an option's price and the underlying PDF. There are several ways to overcome this problem: using the rather tight upper and lower bounds that can be put on American option prices instead of a single equation that relates a European option price to the PDF (Melick and Thomas (1997)), adjusting each American option price to create an artificial European price (Bliss and Panigirtzoglou (2004)), or ignoring the American premium altogether. We choose the last approach to make the presentation of our OLS technique as straightforward as possible and because options on federal funds futures are almost never exercised early, suggesting that the American premium is likely to be very small.[viii]

The second complication is that in the presence of a risk premium, the estimated risk-neutral PDF may not correspond to the real object of interest, the actuarial PDF that has been purged of any distortions brought about by market participants who have over- or underpaid for options on account of an aversion to risk. The problem is equivalent to an attempt to deduce the probability of a fire from the price a homeowner pays for fire insurance. Clearly, a risk-averse homeowner will pay more than the actuarially fair price for fire insurance. Thus an estimate of the probability of a fire based on the price paid for fire insurance will overstate the true probability of a fire. However, as noted earlier, risk premiums in the federal funds futures market are quite small at horizons of one or two months. For this reason, and again to avoid additional complexity, we will interpret the estimated risk-neutral PDFs as good characterizations of the actuarial PDFs, especially when comparing changes in the PDFs from day to day (see Piazzesi and Swanson (2004) on the notion of "differencing out" risk premia.)

The third complication is that the target federal funds rate is an interest rate, but the futures and options prices are quoted in terms of an index that equals 100 minus the federal funds rate, conforming with the convention adopted for Eurodollar futures and options. However, as shown in Appendix 1, subtracting each option's strike price from 100 and reclassifying calls as puts and vice versa transforms options written on 100 minus the federal funds futures rate to options that are written directly on a federal funds futures rate.

With these adjustments, federal funds futures options prices can be expressed mathematically in terms of the target-rate PDF as follows. For European options, the price of the option can be expressed as the discounted value of the option's pay-off. For a call option that finishes in the money, the pay-off is the difference between the underlying asset's price at expiration and the strike price. If the call option finishes out of the money, the pay-off is zero. For a put option that finishes in the money, the pay-off is the difference between the strike price and the underlying asset's price at expiration. If the put option finishes out of the money, the pay-off is zero. Usually, the futures price, F_t, is assumed to be a continuous random variable with density function, $f\left(F_T\right)$. In this standard case, and in a risk-neutral world, discounted call and put prices can be written as

$$\frac{C(t,T,X,F_T)}{e^{-r\cdot(T-t)}} = \int_0^{\infty} \max(0, F_T - X)df(F_T)$$

$$\frac{P(t,T,X,F_T)}{e^{-r\cdot(T-t)}} = \int_0^{\infty} \max(0, X - F_T)df(F_T),$$

where

$t =$ the date on which the option price is observed
$T =$ the date on which the option expires
$X =$ the option's strike price
$F_T =$ the price of the underlying asset (futures rate) at date T
$r =$ the risk-free rate of interest.

However, in the case of options written on federal funds futures, the price of the underlying asset is most appropriately assumed to be a discrete random variable. The price of the underlying asset is the average federal funds rate for the contract month, and this average is almost perfectly determined by interventions in the federal funds market undertaken by the Trading Desk at the Federal Reserve Bank of New York. Such interventions are aimed at keeping the rate equal to the FOMC's target level.

Though the Trading Desk may miss the target on any given day, its average monthly deviation is essentially zero. Importantly, target rates are generally specified in increments of 25 basis points. Moreover, the number of possible federal funds target alternatives that are likely to be considered at any particular FOMC meeting is usually small—most often three or fewer. For example, it is sometimes the case that the FOMC chooses between maintaining the target federal funds rate at its current level, or raising the target level either 25 or 50 basis points. In such a case, the three discrete outcomes would account for 100 percent of the associated probabilities.

In months which include FOMC meetings, the number of possible outcomes would imply the same number of corresponding monthly average outcomes, each based on the day-weighted average of the target rate in place before the meeting and the target rate chosen at the meeting. Of course, we assume here that the target rate before the meeting is known with certainty. This assumption would be violated if policy changes between meeting dates, or if the horizon is extended out further than one meeting. Concerning the first case, it has become extremely rare that policy actions take place between meetings. We thus argue that it is reasonable to assume that rate changes occur only at meeting dates. We deal with the second case in turn.

If there are N possible target rates, each with an associated probability that the FOMC will select that target rate, the price of call and put options can then be written as

$$\frac{C(t,T,X,F_T)}{e^{-r\cdot(T-t)}} = \sum_{i=1}^{N} \pi_i \cdot \max(0, F_{T,i} - X)$$

$$\frac{P(t,T,X,F_T)}{e^{-r\cdot(T-t)}} = \sum_{i=1}^{N} \pi_i \cdot \max(0, X - F_{T,i})$$

where π_i is the probability that the FOMC at its next meeting will select target federal funds rate T_i, in which case the average federal funds rate for the month will take on the value $F_{T,i}$.

On any given day for any options contract, there will be many options that are trading: several calls with different strike prices and several puts with different strike prices. It is straightforward to express the discounted prices of these options in matrix notation. As an example, consider a trading day with five options that are actively traded, three call options and two put options.[ix] For generality, assume that each option has a different strike price. To make the example concrete, suppose the participants in the upcoming FOMC meeting are expected to choose from among three possible targets for the federal funds rate.[x] For this example, the option pricing equations in matrix form are given by

$$\begin{bmatrix} \frac{C(t,T,X_1,F_T)}{e^{-r\cdot(T-t)}} \\ \frac{C(t,T,X_2,F_T)}{e^{-r\cdot(T-t)}} \\ \frac{C(t,T,X_3,F_T)}{e^{-r\cdot(T-t)}} \\ \frac{P(t,T,X_4,F_T)}{e^{-r\cdot(T-t)}} \\ \frac{P(t,T,X_5,F_T)}{e^{-r\cdot(T-t)}} \end{bmatrix} = \begin{bmatrix} \max(0,F_{T,1}-X_1) & \max(0,F_{T,2}-X_1) & \max(0,F_{T,3}-X_1) \\ \max(0,F_{T,1}-X_2) & \max(0,F_{T,2}-X_2) & \max(0,F_{T,3}-X_2) \\ \max(0,F_{T,1}-X_3) & \max(0,F_{T,2}-X_3) & \max(0,F_{T,3}-X_3) \\ \max(0,X_4-F_{T,1}) & \max(0,X_4-F_{T,2}) & \max(0,X_4-F_{T,3}) \\ \max(0,X_5-F_{T,1}) & \max(0,X_5-F_{T,2}) & \max(0,X_5-F_{T,3}) \end{bmatrix} \cdot \begin{bmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \end{bmatrix}.$$

These matrices lend themselves to ordinary least squares (OLS) estimation. In more compact notation we have

$$Y = Z \cdot \pi$$
$$\hat{\pi} = (Z' \cdot Z)^{-1} \cdot Z' \cdot Y.$$

However, this standard OLS estimation does not impose the restriction that the probabilities sum to one, $\sum_{i=1}^{N} \pi_i = 1$. This restriction can be written in matrix form as $r_1 + r_2 \cdot \pi_{sub} = \pi_{res}$, where π_{sub} is a subset of the probabilities. Notice that we do not impose the restriction that the probabilities must lie between zero and one. Such a restriction would require a much more complicated estimation procedure. For the example outlined above, the restriction that the probabilities sum to one would be written in matrix notation as

$$\underset{r_1}{\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}} + \underset{r_2}{\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -1 & -1 \end{bmatrix}} \cdot \underset{\pi_{sub}}{\begin{bmatrix} \pi_1 \\ \pi_2 \end{bmatrix}} = \underset{\pi_{res}}{\begin{bmatrix} \pi_1 \\ \pi_2 \\ 1 - \pi_1 - \pi_2 \end{bmatrix}}.$$

This restriction can be imposed on the OLS estimators as follows[xi].

$$Y = Z \cdot \pi_{res} = Z \cdot (r_1 + r_2 \cdot \pi_{sub}) = Z \cdot r_1 + Z \cdot r_2 \cdot \pi_{sub},$$

which simplifies to

$$Y - Z \cdot r_1 = Z \cdot r_2 \cdot \pi_{sub}.$$

The estimated probabilities are then found as

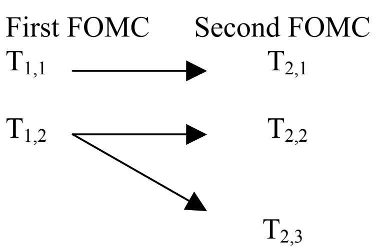
$$\hat{\pi}_{sub} = ((Z \cdot r_2)' \cdot (Z \cdot r_2))^{-1} \cdot (Z \cdot r_2)' \cdot (Y - Z \cdot r_1)$$

and

$$\hat{\pi}_{res} = r_1 + r_2 \cdot \hat{\pi}_{sub}.$$

Therefore, in most cases it will be possible to obtain both an unrestricted and a restricted estimate of the probabilities associated with the possible federal funds targets. This will be true so long as a possible federal funds target rate falls in between the strike prices for all possible pairs of option prices. In some instances, however, it may be the case that two or more of the options that are traded would finish in and out of the money for exactly the same possible federal funds target rates. In this case, two or more of the columns of the matrix Z would be linear combinations of each other because the values in the two columns would be equal to each other plus the difference in strike prices between the two options. Thus, the Z matrix would not be of full rank, and the OLS estimates could not be recovered. The restricted probabilities could still be estimated, so long as only two of the columns were linear combinations of each other.

It is also possible to jointly estimate probabilities for two or more sets of federal funds target rates coming from two or more FOMC meetings. Continuing with a relatively simple example, suppose we have five option prices from one contract where there are two expected target rate outcomes, and we have four option prices from a second contract (later in the year) where there are three expected target rate outcomes. We must introduce a second subscript that denotes whether a target rate is chosen at the first FOMC meeting or the second FOMC meeting. Thus $F_{2,1}$ is the value taken on by the monthly average federal funds rate if $T_{2,1}$ is chosen at the second FOMC meeting. Suppose that the researcher imposes the following structure: If the first target rate is chosen at the first meeting, then there is only one possible choice for the target rate at the second meeting, while if the second target rate is chosen at the first meeting, then either of two target rates can be chosen at the second meeting. This structure can be shown diagrammatically:



Given this structure, the option pricing equations for all nine options (five from the first contract and four from the second contract) are written in matrix notation as

$$\begin{bmatrix} \frac{C(t,T_1,X_{1,1},F_{T1})}{e^{-r(T_1-t)}} \\ \frac{C(t,T_1,X_{1,2},F_{T1})}{e^{-r(T_1-t)}} \\ \frac{C(t,T_1,X_{1,3},F_{T1})}{e^{-r(T_1-t)}} \\ \frac{P(t,T_1,X_{1,4},F_{T1})}{e^{-r(T_1-t)}} \\ \frac{P(t,T_1,X_{1,5},F_{T1})}{e^{-r(T_1-t)}} \\ \frac{C(t,T_2,X_{2,1},F_{T2})}{e^{-r(T_2-t)}} \\ \frac{C(t,T_2,X_{2,2},F_{T2})}{e^{-r(T_2-t)}} \\ \frac{P(t,T_2,X_{2,3},F_{T2})}{e^{-r(T_2-t)}} \\ \frac{P(t,T_2,X_{2,4},F_{T2})}{e^{-r(T_2-t)}} \end{bmatrix} = \begin{bmatrix} m(F_{t1,1},X_{1,1}) & m(F_{t1,2},X_{1,1}) & 0 & 0 & 0 \\ m(F_{t1,1},X_{1,2}) & m(F_{t1,2},X_{1,2}) & 0 & 0 & 0 \\ m(F_{t1,1},X_{1,3}) & m(F_{t1,2},X_{1,3}) & 0 & 0 & 0 \\ m(X_{1,4},F_{t1,1}) & m(X_{1,4},F_{t1,2}) & 0 & 0 & 0 \\ m(X_{1,5},F_{t1,1}) & m(X_{1,5},F_{t1,2}) & 0 & 0 & 0 \\ 0 & 0 & m(F_{t2,1},X_{2,1}) & m(F_{t2,2},X_{2,1}) & m(F_{t2,3},X_{2,1}) \\ 0 & 0 & m(F_{t2,1},X_{2,2}) & m(F_{t2,2},X_{2,2}) & m(F_{t2,3},X_{2,2}) \\ 0 & 0 & m(X_{2,3},F_{t2,1}) & m(X_{2,3},F_{t2,2}) & m(X_{2,3},F_{t2,3}) \\ 0 & 0 & m(X_{2,4},F_{t2,1}) & m(X_{2,4},F_{t2,2}) & m(X_{2,4},F_{t2,3}) \end{bmatrix} \cdot \begin{bmatrix} \pi_{1,1} \\ \pi_{1,2} \\ \pi_{2,1} \\ \pi_{2,2} \\ \pi_{2,3} \end{bmatrix},$$

where, in order to save space,

$$m(F_{t1,1},X_{1,1}) = \max(0, F_{t1,1} - X_{1,1}).$$

Estimating this system via OLS is straightforward and will yield results that are identical to a separate estimation for each of the two FOMC meetings. However, there are three restrictions that can be imposed, given the relationship between the target federal funds rates across the two meetings. First, the probability of the FOMC selecting the target rate $T_{1,1}$ and the probability of the FOMC selecting target rate $T_{1,2}$ must sum to one: that is, $\pi_{1,1} + \pi_{1,2} = 1$. Second, the structure imposed by the researcher (perhaps based on market commentary) implies that if $T_{1,1}$ is chosen at the first FOMC meeting, then $T_{2,1}$ will be chosen at the second meeting, so it must be that $\pi_{2,1} = \pi_{1,1}$. Finally, the sum of the probabilities that target rates $T_{2,2}$ and $T_{2,3}$ will be chosen must equal the probability that target rate $T_{1,2}$ is chosen at the first meeting. That is, $\pi_{2,2} + \pi_{2,3} = \pi_{1,2}$. Notice that these three restrictions also guarantee that $\pi_{2,1} + \pi_{2,2} + \pi_{2,3} = 1$. The restrictions are written in matrix notation as

$$
\begin{array}{ccccccc}
r_1 & + & r_2 & \cdot \pi_{sub} & = & \pi_{res} \\
\begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} & + & \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 1 & 0 \\ 0 & 1 \\ -1 & -1 \end{bmatrix} & \cdot \begin{bmatrix} \pi_{1,1} \\ \pi_{2,2} \end{bmatrix} & = & \begin{bmatrix} \pi_{1,1} \\ 1-\pi_{1,1} \\ \pi_{1,1} \\ \pi_{2,2} \\ 1-\pi_{1,1}-\pi_{2,2} \end{bmatrix}
\end{array}
$$

with the restricted estimation proceeding as above.

III. Estimates of the Implied PDFs

Data on daily settlement prices for federal funds futures and options were obtained from the CBOT for the period January 1, 2003, through September 22, 2004. Settlement prices are used to avoid stale and asynchronous quotes. This data set contained 5,092 futures prices and 28,104 option prices. Option prices were then checked for violations of options selling for less than their exercise value, monotonicity and concavity when plotting option price against the strike price, changes in option prices that were greater than changes in the strike price when comparing options with different strike prices for a given contract on a single day, and put-call parity. All told, 218 options were found to violate these conditions, so roughly 0.8 percent of the data were eliminated. The risk-free rate of interest was set equal to the yield on the Treasury bill that matured as few days as possible after the expiration of each option contract.[xii]

Single FOMC Meeting Estimation

Each options contract that expired before November 2004 (May 2003 through October 2004) was used to recover the PDF for the target federal funds rate ahead of a single FOMC meeting. That is, each contract was assigned a single FOMC meeting outcome that it was to "predict." A PDF was recovered each day for each contract, although days were deleted under the following conditions. First, a day was deleted if it had fewer than five options with prices that were above the minimum price of one-quarter of a basis point.[xiii] Second, days were deleted that fell after the FOMC meeting that the contract is predicting. For example, days after June 25, 2003, were deleted for the July 2003 contract, since the July contract was used only to predict the outcome of the June 25, 2003, FOMC meeting. Third, days were deleted if they had one (or more) FOMC meetings before the FOMC meeting that the contract is predicting. For example, days before the May 6, 2003, FOMC meeting for the July 2003 contract were deleted, again since the July 2003 contract was used only to recover a PDF for the outcome of the June 25, 2003, FOMC meeting. Finally, the June 2004 contract was not used because the second day of the June 2004 FOMC meeting fell on the last day of the month, meaning that the June 2004 FOMC decision would have almost no effect on the monthly average federal funds rate. These deletions left a data set of 434 days (and futures prices) and 6,377 options prices across 14 contracts.

Table 1 presents descriptive statistics for this data set by contract, including details on which FOMC meeting was assigned to which contract and the number of daily PDFs recovered for each contract. Each contract was used for about six weeks ahead of the FOMC meeting it was predicting, so each contract generated about 30 PDFs. Almost 46 percent of the options used in estimation were calls. The September 2004 contract had the most options traded per day. Strike prices for the options ranged from a low of 0.25 percent to a high of 2.00 percent. Between the conclusion of the June 2003 FOMC meeting and the June 2004 FOMC meeting, there was little expectation of another change in the FOMC target rate, with little variability in the futures price for the September 2003 through May 2004 contracts.

Figure 3 contains a recovered PDF for a trading day in which probabilities for five policy outcomes were estimated, although two of the outcomes appear to be irrelevant. According to the estimates, as of May 27, 2003, market participants saw a roughly 20 percent chance that the FOMC would reduce the target federal funds rate from 1.25 to 0.75 percent on June 25, 2003, at the conclusion of its two-day meeting. Market participants saw a 30 percent chance that the FOMC would reduce the target rate from 1.25 to 1.00 percent and a 50 percent chance that the target federal funds rate would remain unchanged at 1.25 percent. Consistent with market commentary at the time, market participants saw essentially no chance of a 75 basis point reduction or 25 basis point increase in the target rate.

Estimates like those in Figure 3 were obtained for the 434 contract days summarized in Table 1. For each day, the call with the highest strike and the put with the lowest strike were used to assign the possible target rate outcomes. The highest strike price for the calls was rounded up to the nearest multiple of 25 basis points, and the lowest strike price for the puts was rounded down to the nearest multiple of 25 basis points. This algorithm establishes the range for the target rate outcomes, with all intermediate 25 basis point multiples filled in. Taking Figure 3 as an example, on May 27, 2003, the call with the highest strike was 1.25 and the put with the lowest strike was 0.625. Thus, the estimated PDF has five possible outcomes, ranging from 0.50 to 1.50 in 25 basis point increments.

Summary statistics for all of the 434 estimated PDFs are presented in Table 2. The top panel of the table reports results for unrestricted estimation of the probabilities while the bottom panel reports results when imposing the restriction that the probabilities sum to one. The R^2 statistics are uniformly high, with little drop-off in goodness of fit when the restriction is imposed. Under the assumption of risk-neutrality, it should be the case that $F_t = \sum_{i=1}^{n} \hat{\pi}_i \cdot F_{T,i}$, that is the futures price should be equal to the mean of the PDF. In fact, this restriction could also be imposed on the OLS estimates. We chose to save the futures price for the above out-of-sample comparison to the mean of the PDF. For the estimates that do not impose the restriction that the probabilities sum to one, the mean of the PDF is quite close to the futures price, usually well within two basis points. The relatively large misses for the May 2003 contract are probably not due to pricing anomalies associated with the introduction of the new options contract, since the mean for the restricted estimates for May (bottom panel of the chart) are quite close to the futures price. For all but two of the eleven contracts, the mean of the PDF from the restricted estimates does a better job, on average, of matching the futures price. These means from the restricted estimates are almost always within $1/10^{th}$ of basis point of the futures price.

Figure 4 summarizes the evolution over time of estimates of the probabilities associated with alternative June 2003 FOMC meeting outcomes. The procedure allows for five possible outcomes: no change; rate cuts of 25, 50, and 75 basis points each; a rate hike of 25 basis points. Immediately after the

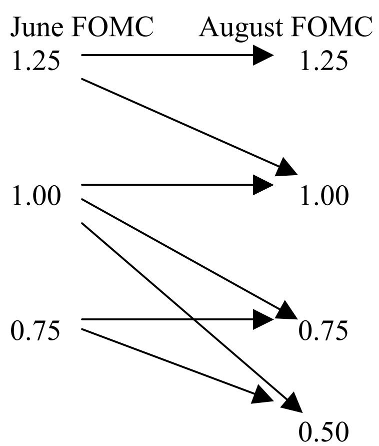
May meeting, options prices indicated that probability of the no-change outcome exceeded 60 percent. Uncertainties surrounding the war in Iraq had been diminishing, and forecasters anticipated an acceleration in economic activity. As the summer approached, however, incoming data failed to clearly confirm such expectations, and the prospect of a rate cut became more likely. Indeed, markets began to entertain a remote possibility of a 75 basis point rate reduction. The prospect of a rate increase was never given much of a chance.

Around mid-May the probability of no cut fell below 50 percent. However, Chairman Greenspan's May 19 testimony before Congress was interpreted as being relatively upbeat, and the trend reversed some, stabilizing around even odds for a rate reduction versus no change. By early June, relatively disappointing economic news raised concerns that FOMC might need to reduce the federal funds rate further as an insurance measure to avoid a small probability that a general deflation might emerge. The perceived tone of a June 3 satellite speech by Chairman Greenspan to foreign central bankers heightened such concerns, as did a subsequent speech by Governor Kohn. Within a week or so, the prospect of a further cut was estimated to be virtually certain. The only issue was whether the cut would be 25 or 50 basis points, with the options pricing structure giving both outcomes about equal probability.

It is worthwhile to note that the May-June 2003 intermeeting period highlights the advantage that our technique provides over using a simple approach based only on the federal funds futures price. For example, consider the futures price on May 6, which implied a yield of 1.10 percent, or more than half way between no change and a 25 basis point cut. Assuming that those were the only two possible outcomes, one is led to believe that a rate cut was likely. The structure of options prices, however, suggested that a 50 basis point change was also a possible outcome. Indeed, its estimated probability was even more likely than that of a 25 basis point change. Our approach allows the data to speak, and they indicate that although the federal funds futures price was more than halfway toward a rate cut, the prospect of no cut was more likely.

Joint FOMC Meeting Estimation

As noted in Section II, a joint estimation of the PDFs for two or more FOMC meetings requires the researcher to impose a structure on the potential paths that the FOMC might follow when setting the target federal funds rate. We have not yet developed an algorithm for generating these structures that would enable us to conduct a joint estimation for every day in the data set. Instead, we simply present a single day's estimation in order to provide an example of a joint estimation. Ahead of the June 25, 2003, FOMC meeting the target federal funds rate stood at 1.25 percent. To perform the estimation, we imposed the following structure on the possible paths for the target rate from the June 25, 2003, to the August 12, 2003, FOMC meetings. Note that we ruled out the possibility of a 50 basis point rate cut in August if there had been no change in the target rate at the June meeting.



Settlement options prices from May 27, 2003, for the July 2003 and August 2003 contracts were used to estimate both the unrestricted and restricted probabilities for the paths, with results shown in Table 3, and the restricted results plotted in Figures 5a and 5b.

The jointly estimated results for the June 25, 2003, FOMC meeting are slightly different than the results presented in Figure 3, as five possible outcomes for the June FOMC meeting were allowed for in Figure 3, while only the three most likely outcomes were allowed for in the results shown in Table 3 and Figures 5a and 5b. Nevertheless, it is reassuring that the joint estimates are not much different than the single estimates, both indicating roughly a 50 percent chance of the target rate remaining at 1.25 percent in June, roughly a 30 percent chance of the target rate being reduced to 1.00 percent, and roughly a 20 percent chance of the target rate being reduced to 0.75 percent.

Notice from the third column of Table 3 that it is possible to obtain a negative estimate for one of the probabilities (in this case the probability that the target rate would remain at 1.25 percent in June and be cut to 1.00 percent in August.) There is nothing in the OLS estimation that prevents a negative probability. The last column of Table 3 presents the restricted estimates, where a negative probability is no longer a problem.

Our estimation procedure imposes several restrictions. First, the probabilities for the three possible outcomes from the June meeting must sum to one. Second, the probabilities for the two outcomes for the August meeting, conditional on a choice of 1.25 percent for the target rate at the June meeting, must sum to the unconditional probability of a target rate of 1.25 percent being chosen at the June meeting. This is indeed the case, as 0.50422 plus 0.01038 equals 0.51460. Third, the probabilities for the three outcomes for the August meeting, conditional on a choice of 1.00 percent for the target rate at the June meeting, must sum to the unconditional probability of a target rate of 1.00 percent being chosen at the June meeting. Finally, the probabilities for the two outcomes for the August meeting, conditional on a choice of 0.75 percent for the target rate at the June meeting, must sum to the unconditional probability of a target rate of 0.75 percent being chosen at the June meeting. All of these restrictions also imply that the probabilities for all of the August outcomes will sum to one.

IV. Comparing Options-Based PDFs with Futures-Based Probabilities

As noted in the introduction, it is quite common to use prices from federal funds futures contracts to recover the probabilities associated with target federal funds rates that might be chosen by the FOMC at upcoming meetings. Of course, this procedure is limited, since a single futures price can be used to recover only two probabilities. However, if the FOMC is believed to be choosing from only two alternatives, the procedure is appropriate.[xvi] In any event, it is instructive to compare the probabilities estimated from options prices to those recovered from futures prices. If the probabilities are the same, or if it can be shown that the futures-based probabilities are in some sense superior, then analysts should not spend the extra time and effort needed to estimate the probabilities using options prices.

To recover probabilities from futures prices we solved the following equation

$$Futures_{i,t} = \left(\frac{DB_{i,y}}{TD_{i,t}}\right) \cdot CTFF_{i,t} + \left(\frac{DA_{i,y}}{TD_{i,t}}\right) \cdot \left(\pi^{L}_{i,t} \cdot TFFL_{i,t} + \pi^{H}_{i,t} \cdot TFFH_{i,t}\right),$$

where

$$TFFL_{i,t} = \begin{cases} CTFF_{i,t} + 25\text{ bp} & \text{if} \quad Futures_{i,t} > \left(\frac{DB_{i,t}}{TD_{i,t}}\right) \cdot CTFF_{i,t} + \left(\frac{DA_{i,t}}{TD_{i,t}}\right) \cdot \left(CTFF_{i,t} + 25\text{ bp}\right) \\ CTFF_{i,t} & \text{if} \quad CTFF_{i,t} < Futures_{i,t} \le \left(\frac{DB_{i,t}}{TD_{i,t}}\right) \cdot CTFF_{i,t} + \left(\frac{DA_{i,t}}{TD_{i,t}}\right) \cdot \left(CTFF_{i,t} + 25\text{ bp}\right) \\ CTFF_{i,t} - 25\text{ bp} & \text{if} \quad \left(\frac{DA_{i,t}}{TD_{i,t}}\right) \cdot \left(CTFF_{i,t} - 25\text{ bp}\right) + \left(\frac{DB_{i,t}}{TD_{i,t}}\right) \cdot CTFF_{i,t} < Futures_{i,t} \le CTFF_{i,t} \\ CTFF_{i,t} - 50\text{ bp} & - \quad \text{otherwise} \end{cases}$$

$$TFFH_{i,t} = TFFL_{i,t} + 25\text{ bp},$$

subject to the restriction that $\pi_L + \pi_H = 1$, and where

$Futures_{i,t} = (100 \text{ - the futures price for contract } i \text{ on day } t)$

$DB_{i,t}$ = days in the month before the FOMC meeting predicted by contract *i* on day *t*

$DA_{i,t}$ = days in the month after the FOMC meeting predicted by contract *i* on day *t*

$TD_{i,t}$ = total days in the month of the FOMC meeting predicted by contract *i* on day *t*

$CTFF_{i,t}$ = current target federal funds rate (i.e., that is, before the FOMC meeting) for contract *i* on day *t*

$TFFL_{i,t}$ = lowest target federal funds rate that might be selected at the upcoming FOMC meeting for contract *i* on day *t*

$TFFH_{i,t}$ = highest target federal funds rate that might be selected at the upcoming FOMC meeting for contract *i* on day *t*

$\pi^{L}_{i,t}$ = the probability associated with $TFFL_{i,t}$ for contract *i* on day *t*

$\pi^{H}_{i,t}$ = the probability associated with $TFFH_{i,t}$ for contract *i* on day *t*.

The probabilities $\pi^{L}_{i,t}$ and $\pi^{H}_{i,t}$ can then be compared to the probabilities estimated from options prices for the same alternative target federal funds rates. Table 4 contains the results of simple t-tests for a difference in means across two populations when comparing the probabilities estimated from options prices to those recovered from futures prices. Comparisons are made by individual contract as well as for all contracts treated as a whole. For the comparison by contract, in only 6 out of the 28 possible comparisons do we fail to reject at the five percent level of significance the null hypothesis that the probabilities are drawn from the same population. Taking all contracts together, the null of the same population is rejected at any conventional level of significance. It is apparent that the two methods are returning probabilities that are statistically different from each other. Notice that there is a discernable time pattern to the size of the differences between the options probabilities and the futures probabilities. In particular, the probabilities are most different for the May, June, and July 2003 contracts, a period in which it was likely that there were more than two possible target federal funds rates in play. For later contracts, when the direction and magnitude of future target rate changes was much clearer, there is little difference between the probabilities. For contracts after July 2003, the difference usually amounts to only around five percentage points.

Of course, the question remains whether one set of probabilities is in some sense superior to the other. To shed some light on this issue, we compare the forecasting performance of the two probabilities. Results of an extremely simple-minded comparison are found in Table 5, which contains the conventional calculation of root mean squared forecast errors (RMSE). Using RMSE, the futures probabilities would be judged as superior to those from options. As discussed in Appendix 2, however, the RMSE criterion is an inappropriate means to judge densities. By design, it heavily favors any density that is based on the assumption that the FOMC will choose from only two alternatives. Thus, the futures-based forecasts will enjoy a considerable advantage. We hence view the results of Table 5 as misleading and conclude that they should not be used to argue that the futures-based probabilities are superior.

We recognize that the FOMC most often considers only two alternative target rates. Thus, probabilities from the fed funds futures contract should *usually* offer superior predictive content. However, we would emphasize that when the two estimates differ significantly, options-based forecasts can be particularly instructive. This situation occurs when there are more than two outcomes in play as illustrated in Figure 4. As the meeting date approached, options-based PDFs revealed a fairly diverse and dynamic change of market opinion. Moreover, the estimated PDF on May 27, 2003, revealed in Figure 3 indicates that the no-policy-change alternative (keeping the target rate at 1.25) was the most likely outcome. The fed funds rate futures estimate, on the other hand, indicated that a 25 basis point rate cut outcome was near certain. We thus conclude that market participants, at a minimum, will want to confirm that the simpler futures-based probabilities are appropriate by comparing them to options-based probabilities.

No matter what comparison method is used, however, we have only a very small sample of 14 contracts at our disposal. Given this sample size, we are unable to make any strong statements about the superiority of options or futures based probabilities.[xvii] We can say that they are different, and those differences are largest at times when market commentary suggests that the FOMC is seen to be choosing from more than two possible target federal funds rates.

V. The Impact of Information and Federal Reserve Communication on Estimated Probabilities

The preceding sections of the paper have demonstrated that options on federal funds futures can be used to recover the market's assessment of the probabilities associated with possible outcomes for upcoming FOMC meetings. Obviously, these recovered probabilities contain useful information about market expectations, but they also provide a unique measure that can identify what information shapes market expectations and quantify the quality ("transparency," in policy jargon) of communication between the FOMC and the market.

Since the early 1990s the Federal Open Market Committee has adopted several changes in its procedures and communications designed to improve transparency (see Greenspan [2001]). Swanson (2004) shows that since the 1980s, U.S. financial markets and private sector forecasters have become better able to forecast the federal funds rate at horizons out to several months and have been less surprised by Federal Reserve announcements. A key implication of this analysis is that financial market forecasters understand what information is likely to guide actual policy actions, and they react to it in a consistent way.

It has become widely known that the FOMC reacts systematically (though not exclusively) to information about inflation and economic activity in a manner identified by John Taylor. In simple terms, this relationship—the so-called Taylor rule—is characterized by an equation that implies that the fed funds rate tends to increase (decrease) with information indicating a strengthening (weakening) in economic activity relative to potential and to decrease (increase) with the difference between inflation and some implied target rate. At any point in time futures and options prices might be expected to fully reflect all information about the economy and inflation. We should thus expect surprises in data releases on employment and inflation to be associated with immediate changes in the probability distribution of alternative outcomes of future FOMC meetings.

The estimated probabilities for alternative June 2004 outcomes in Figure 6 provide a clear illustration. During 2003, unusually slow employment growth raised doubts about the sustainability of the economic expansion. Moreover, it was thought that if employment growth did not begin to rise soon, the economy might be at risk of deflation. As a consequence, the target fed funds rate had been reduced to one percent, a level viewed as accommodative. At the August 2003 meeting, the Committee adopted language that indicated that the FOMC would not likely remove its accommodative stance for a considerable period. The market for options of fed funds futures was largely inactive, offering few options at alternative strike prices. Estimates of the probability of no change in policy for the upcoming meeting ranged between 90 and 100 percent from late summer through early spring.

As illustrated in Figure 6, things began to change with the release of the April 2004 *Employment Situation*. Estimates of the probability distribution of possible outcomes for the June FOMC meeting revealed an increasing likelihood of a rate hike as a series of two strong employment reports indicated that the recovery was gaining traction. When the May employment report was released in early June, the estimated probability for no change fell to around 5 percent—less than the estimated probability for a 50 basis point rate hike.

It is quite clear that, at times, the release of new economic data (such as the monthly *Employment Situation* or *Consumer Price Index* reports) can change market views of the target federal funds rate likely to be selected at the upcoming FOMC meeting. It could also be the case that market views are influenced by speeches and testimony given by Federal Reserve officials. The above descriptions of reactions to the arrival of information raise the question of whether or not there is a systematic relationship between market views and the arrival of new information. The probability estimates recovered from options prices provide a means of exploring the existence of such a systematic relationship.

To address this issue, we define $\pi_{i,t}^{A}$ as the ex ante probability (estimated from options contract i on day t) that the ex-post actual FOMC target rate would be chosen at the upcoming FOMC meeting. Thus, $\pi_{i,t}^{A}$ is the probability, as of day t, that the market placed on the FOMC choosing the target rate that actually was chosen. We posit the following regression:

$$\begin{aligned}\pi_{i,t}^{A} = {} & \alpha_1 \cdot \pi_{i,t-1}^{A} + \alpha_2 \cdot CumCPI_{i,t} + \alpha_3 \cdot CumEMP_{i,t} + \alpha_4 \cdot CumFedTes_{i,t} + \alpha_5 \cdot CumFedCom_{i,t} + \\ & \alpha_6 \cdot DaysBefFOMC_{i,t} + \alpha_7 \cdot DaysBefFOMC_{i,t} \cdot \pi_{i,0}^{A} + \alpha_8 \cdot \left(CP_{i,t} \cdot CumCPI_{i,t}\right) + \\ & \alpha_9 \cdot \left(CP_{i,t} \cdot CumEMP_{i,t}\right) + \alpha_{10} \cdot \left(CP_{i,t} \cdot CumFedCom_{i,t}\right) + \mu_i + \varepsilon_{i,t},\end{aligned}$$

where

$CumCPI_{i,t}$ = the cumulative number of CPI reports released during contract i's period of observation up to day t.

$CumEMP_{i,t}$ = the cumulative number of employment reports released during contract i's period of observation up to day t.

$CumFedTes_{i,t}$ = the cumulative number of testimonies on economic conditions by the Federal Reserve chairman during contract i's period of observation up to day t.

$CumFedCom_{i,t}$ = the cumulative number of speeches on economic conditions by the Federal Reserve chairman during contract i's period of observation up to day t.

$DaysBefFOMC_{i,t}$ = the number of days until the FOMC meeting predicted by contract i on day t.

$CP_{i,t}$ = a dummy variable that equals one if day t for contract i falls in the period during which the FOMC press release used the language "considerable period" (August 12, 2003, through January 27, 2004).

Descriptive statistics on these variables are reported in Table 6. The presumption is that new information should increase the ex ante probability associated with the target rate that will actually be chosen by the FOMC. In terms of the equation, if new information is revealed that is pertinent to future FOMC decisions, then coefficients α_2 through α_5 should be positive. This new information can take the form of data releases and testimony or commentary from the Federal Reserve chairman. The passage of time might also affect the ex ante probability. As an FOMC meeting approaches, the market may become more informed about the intentions of the FOMC, through a variety of sources not considered above. Because the right-hand-side variables do not capture all of the information flowing to market participants, information gained from other sources would be revealed over time—the so-called secular effect. We measured time as days before the FOMC meeting, so as we approach the meeting, this variable is taking on smaller values. Hence, if the passage of time allows market participants to better understand FOMC intentions, α_6 should be negative, since the probability of the actual outcome should increase as the days before the meeting diminish. We also interact the passage of time with the initial ex ante probability from the first day of the contract ($\pi^A_{i,0}$) to allow time to have different effects that depend on how far market expectations are away from the target that will eventually be chosen. The coefficient on this interaction term, α_7, should also be negative.

Finally, when it is clear that the FOMC has signaled that it does not plan any policy changes at an upcoming meeting, the arrival of new information may be of no value for the estimated probability distribution. Such might have been the case between mid-August 2003 and late January 2004, when FOMC statements included the sentence "In these circumstances, the Committee believes that policy accommodation can be maintained for a considerable period." The period leading up to the December 2003 meeting illustrates the point (see Figure 7). Markets expected no action by FOMC during the whole intermeeting period, effectively ignoring information that would have otherwise affected the policy outcome.

To account for the effects of this kind of "steering language," we create a dummy variable that equals one during this period and zero otherwise and then interact that dummy with our information variables.[xviii] If new information was of no value when the "considerable period" language was in effect, then it should be the case that $\alpha_2 = -\alpha_8$, $\alpha_3 = -\alpha_9$, $\alpha_4 = -\alpha_{10}$; hence, effectively shutting off normal systematic effects.

Fixed-effects-estimation results for the regression model are found in Table 7. We present three sets of OLS results; the first two columns do not include the lagged dependent variable as an explanatory variable.[xix] The third column is presented to assuage fears that our results are sensitive to a more dynamic specification. Looking across the three columns, the CPI and employment variables are always positive, as expected, and significant at standard levels. They also appear to be economically significant. Using the results in the second column, both a new CPI release and a new employment release are associated with a roughly 4 percentage point increase in the ex ante probability associated with the target rate actually chosen by the FOMC.

Interestingly, Congressional testimony presented by the chairman in two of the three regressions does not have a statistically significant effect on the ex ante probability. It may be that the chairman's testimonies, which are scheduled well in advance, offer relatively little new information to the market. In contrast, the positive and significant coefficient on the chairman's speeches in all three specifications indicates that this information moves the market closer to the target rate that will be chosen by the FOMC. Moreover, the speeches have an economically meaningful effect. Each speech by the chairman is associated with at least a 5 percentage point increase in the ex ante probability associated with the target rate actually chosen by the FOMC.

We also find evidence of a secular trend effect. The passage of time enters significantly in the first two regressions, while the lagged dependent variable does so in the third. Just as one might expect, information not measured by the explicit information explanatory variables finds its way into our estimates of the PDFs. As an upcoming FOMC meeting approaches, the probability associated with the choice ultimately made by the FOMC increases. The interaction term in the second regression indicates that the effect of the passage of time is larger when market expectations initially attach a low probability to the target rate ultimately selected by the FOMC. For all of these results, it should not be forgotten that these data only cover the period from May 2003 to September 2004, quite obviously a small sample, and yet the observed information affects the probabilities so significantly.

The "considerable period" language appears to change the way in which the market responds to new information. As expected, the coefficients on the considerable period interaction terms are of the opposite sign and of roughly equal magnitude of the information variables, although usually only significant at marginal levels. Taken together, the coefficients on the interaction variables suggest that when the FOMC was using the considerable period language, the arrival of new information had no effect on market views of the target rate to be chosen by the FOMC. That is, the considerable period language seemed to turn off the normal incremental effect of information. We also estimated an alternative specification that used the absolute deviation of the ex ante mean of the PDF from the ex post target rate as the dependent variable. In this specification, the CPI and employment variables remained statistically significant, although their signs changed as a data release narrowed the difference between the ex ante mean and the ex post target rate, as opposed to raising the probability associated with the ex post target rate. In this regression, a new data release brought the ex ante mean about one basis point closer to the ex post target rate. We report the specification with the ex ante probability as the dependent variable since there can be days where there is a dramatic change in the ex ante probability but little change in the mean of the PDF.[xx] Thus, the specification with the absolute deviation as the dependent variable can miss instances where new information has a dramatic impact on market views.

Although covering a very short period of time, these results suggest that the market expects the FOMC to react to inflation and employment in a manner consistent with the Taylor rule. In addition, the market pays considerable attention to, and correctly interprets, commentary by the chairman. We would stress, however, that these results are very preliminary. Nevertheless, we believe they offer some measure of validation for the usefulness of options-based PDFs in assessing the impact of information and Fed communication on expected policy outcomes.

VI. Conclusions

Options on federal funds futures provide a simple but powerful means for extracting market expectations for the possible outcomes of FOMC meetings. This paper demonstrates that options on federal funds futures can provide more information than the common extraction of FOMC probabilities from the prices of federal funds futures contracts. Such situations arise when investor opinion entertains more than two possible outcomes for an upcoming FOMC meeting. An estimator for a PDF for an array of federal funds rate outcomes from a single FOMC meeting is presented. Moreover, we develop a procedure to jointly estimate PDFs for two or more upcoming meetings. Both single and joint estimators use simple OLS regressions to recover the parameters of the PDFs, and these regressions easily incorporate restrictions on the recovered parameters.

The techniques presented in the paper should be of interest to market participants and policy makers who want to obtain a sense of the "market's consensus view" on the future stance of monetary policy. Although probabilities extracted from federal funds futures alone are often sufficient, we highlight estimates from recent episodes that demonstrate the additional informational content of options-based estimates. We conclude that options-based PDFs are most useful during periods of heightened uncertainty about the future course of monetary policy. Finally, even when it is appropriate to assume only two outcomes for policy and use only federal funds futures to extract probabilities, the options-based estimators presented above provide confirmation of the assumption implicit in the futures-based estimator.

Endnotes

[i] Survey data and betting lines also offer assessments of the probabilities of alternative target rate choices at upcoming FOMC meetings. These data are often proprietary and are usually only available in the few days before an FOMC meeting. For an example, see http://www.biz.uiowa.edu/iem/markets/fedpolicyb.html.
[ii] Carlson, Melick and Sahinoz (2003) provide a more extensive discussion of this limitation. See the Wall Street Journal Markets Data Group (2004) for a particularly ambitious example of extracting probabilities from only federal funds futures prices.
[iii] See Chang and Melick (1999) for a survey of the many techniques used to recover PDFs.
[iv] These papers follow a long tradition of empirically estimating the process of monetary policy change, including Rudebusch (1995) and Goodhart (1997).
[v] The Board of Governors of the Federal Reserve Web site (www.federalreserve.gov) provides a listing of changes in the intended federal funds rate from 1990 to the present.
[vi] See Carlson, McIntire and Thomson (1995) and Krueger and Kuttner (1996) for a more detailed description and analysis of predictive content.
[vii] Though the small prediction bias is often treated as a risk premium, it is not clear what it is. It is likely that hedgers are on both sides of the futures market. Nevertheless, we will follow the convention and refer to the bias as a risk premium.
[viii] Practitioners could always modify our technique using either of the two adjustments. The simplest modification would be to use the Barone-Adesi Whaley method to convert the American option prices into European option prices.
[ix] As will be shown below, for our data set there are usually roughly 10 options that were actively traded.
[x] As discussed below, in the actual estimation we let the range covered by the strike prices for the available options determine the number of possible target rates.
[xi] This restricted estimator is different than the typical OLS restricted estimator presented in textbooks (see for example Schmidt (1976)) for the model $Y = X\beta + \mu$ with the restriction $R\beta = r$. This standard restricted estimator is $\tilde{\beta} = \hat{\beta} + (X'X)^{-1}R'\left(R(X'X)^{-1}R'\right)^{-1}\left(r - R\hat{\beta}\right)$, which requires the unrestricted estimator $\hat{\beta}$. If not many federal funds futures options are trading, the unrestricted estimator may not be available, hence the need for an alternative restricted estimator that does not require the unrestricted estimator.
[xii] The largest gap between the expiration of the options contract and the maturity of the Treasury bill was seven days.
[xiii] Options with the minimum price of one-quarter of a basis point ($10.42 given the $5,000,000, 30-day deposit specified in the contract) are informative, essentially indicating that there is no chance of the fed funds rate finishing above (below) the strike price for the call (put) option. However, beyond August 2003, when market participants saw little chance for a change from the current target rate of 1.00 percent, volume dried up in the options market and almost every out-of-the-money option price was at the minimum. The PDF had become degenerate, with all the mass centered at 1.00. The matrix $(z'\cdot z)^{-1}$ becomes almost singular, and the OLS estimates are unstable and unreliable. Requiring five or more non-minimum option prices overcomes this problem. The October 2003, November 2003, and January 2004 contracts never had a day with five or more options with non-minimum prices.
[xiv] The unrestricted estimates are virtually identical and can be found in the working paper version of this article at http://www.clevelandfed.org/Research/Workpaper/Index.cfm.
[xv] In fact, this restriction could also be imposed on the OLS estimates. We chose to save the futures price for the above out-of-sample comparison to the mean of the PDF.
[xvi] Of course, appropriate in as much as a term or risk premium can be ignored or adequately modeled.
[xvii] The problem is that distinguishing a forecast density from the density of the realized outcome is a subtle distinction, one that requires a data set larger than 14 observations.
[xviii] We could not interact the considerable period dummy with all our information variables, as in one case such an interaction generated perfect colinearity for at least one of the contract cross sections.

[xix] Our results are robust to more sophisticated regression techniques. First, statistical significance is little changed when we use standard errors that have been corrected for the relatively small sample size (using the technique proposed by Bond and Windmeijer (2003), given that we have only 14 cross-sectional units with an average of 31 time periods). Second, our inference is unaffected when we use a 2SLS fixed-effects estimator that controls for the possible endogeneity induced by the lagged dependent variable. The 2SLS estimator uses all exogenous right-hand side regressors and 10 of their lags as instruments in the first stage.

[xx] For example, suppose initially that for the next FOMC meeting market participants see a 10 percent chance of a 25 basis point rate cut, an 80 percent chance of no change in the target rate, and a 10 percent chance of a 25 basis point rate increase. Suppose further that on the next day a CPI release leads market participants to now see a 1 percent chance of a 25 basis point rate cut, a 98 percent chance of no change in the target rate, and a 1 percent chance of a 25 basis point rate increase. For this example, there would be no change across the two days in the absolute deviation of the ex ante mean of the PDF from the ex post actual target rate.

Appendix 1

Converting a call option written on an index into a put option written on an interest rate

$P =$ Index value (for example 99)
$i =$ Equivalent interest rate (for example 1.00) $= 100 - P$
$X =$ Strike Price expressed in terms of the index value
$C(P, X) =$ Value of call option with strike price X and index value for the underlying asset of P
$P(i, 100 - X) =$ Value of put option with strike price 100 - X and underlying asset of interest rate i.

The call's price can be written as the probability that it finishes in the money multiplied by the expected payoff given that it finishes in the money.

$$Call(P, X) = \Pr[P > X] \cdot (E[P \mid P > X] - X)$$

let $i = 100 - P$, *so that*

$$\Pr[P > X] = \Pr[i < 100 - X]$$

and

$$E[P \mid P > X] = E[100 - i \mid i < 100 - X] = E[100 \mid i < 100 - X] - E[i \mid i < 100 - X] = 100 - E[i \mid i < 100 - X].$$

Therefore

$$Call(P, X) = \Pr[i < 100 - X] \cdot (100 - E[i \mid i < 100 - X] - X)$$

$$Call(P, X) = \Pr[i < 100 - X] \cdot ((100 - X) - E[i \mid i < 100 - X]) = Put(i, 100 - X).$$

Appendix 2

Two major issues characterize our evaluation of the densities as forecast densities: the fact that our probability models are discrete (and have no convincing continuous approximation) and our sample is very small (and thus we have little recourse to asymptotic theory). This appendix will first explore the inadequacy of a traditional method of forecast evaluation.

We are testing individual densities as models of the actual forecast densities at the time, so that traditional methods of evaluating forecasts (such as mean squared errors) are inappropriate. To illustrate this well-known fact, we use the following example of a density, which is actually the true density and which places a probability of ε on each of $x - 1$ and $x + 1$, and a probability of $(1 - 2\varepsilon)$ on x, where $\varepsilon \leq 0.5$. Unlike our more complicated problem, the densities here are stable over time, so that each draw is from the same density. If we evaluate the density based on average mean squared error, then the true density does less well (both in average small samples and asymptotically) than a forecasting density that places a probability of 1 on x. (The expected mean squared error on the true density exceeds the mean squared error on the false density by $4\varepsilon + \varepsilon(1 - \varepsilon)$.) This aspect about forecasts is well known: To minimize the expected mean squared error, the density should place a point estimate on the expected value of x, rather than try to approximate the true density.

Our tests, by contrast, emphasize the entire density. Our tests are tempered by the fact that our support is not only finite, but small. Thus the z-transformation (based on continuous density functions) is inappropriate for our densities. Instead our tests are based around the following observations: If our probabilities are indeed good forecasting densities, then under the null,

$$(1)\quad E\sum_{n}\frac{I(j)}{n}=\sum_{n}\frac{P_j}{n},$$

where $I(i)$ is the indicator function indicating that event "i" actually happened, and P_i is the probability that it happened. In large samples, one could build a test using asymptotics, and the fact that the variance of the sum of the indicator functions divided by n is easily computed using

$$(2)\ Var\sum_{n}\frac{I(j)}{n}=\sum_{n}\frac{P_j(1-P_j)}{n}.$$

However, our sample size is too small, so we take advantage of the fact that all of our null probabilities are known, so that we can use Monte Carlo to calculate the number of times the summed indicator function could be as large or as small as our sample's under the null.

Equations (1) must hold for any set of events $j \in J$, and equation (2) will hold if the events are independent, which, of course, they will not be if they are the same event! Indeed, for each outcome, one of the non-zero probability events is redundant in the sense that its indicator and probabilities are perfectly dependent on the other indicators and probabilities for that outcome. Thus, we cast out the largest probability for each outcome in constructing our statistic. Then we construct our statistic,

$$(3)\ S\equiv\left(\sum_{n}\frac{I(j)}{n}-\sum_{n}\frac{P_j}{n}\right)^2.$$

To see how this relates to the options and futures implied densities, consider a simple example where the true density (which is the option-implied density as well) places a probability of 0.2 on the rate of 0.75, 0.7 on the rate of 1.00, and 0.1 on the rate of 1.25. In this risk-neutral world, the futures price is 0.975, which gives an implied futures density of 0.9 on the rate of 1.00 and 0.1 on the rate of 0.75. Our test could be formulated with the set J in several ways. In the case of the options density, one could test whether the indicator function for the outcome of 0.75 came up approximately 20% of the time, or we could look at all outcomes with a probability of less than 0.5 (in this case, the events 0.75 and 1.25) to see if the indicator function for these two events, divided by the number of observations *times 2* (remember that two probabilities are in the set J) is equal to 0.15 (or the sum of probabilities divided by their number.) The largest probability mass, 0.7 on the rate 1.00, is not included in set J because it has no information content beyond what is given by the other two probabilities (because the probabilities add up to one). The futures density could be rejected (with a large enough sample) not only because of the positive probability of a rate of 0.75 being set, but also because the rate of 1.25 will be set in the long run higher than what is predicted by the density. Conversely, the rate 1.00 will have a long-run frequency of lower than 90% of the sample observations. Of course, each observation has a separate density, so the set of probabilities, J, must be chosen with some care, especially so that the probabilities, P_i, are similar to one another.

We compute the statistic for several different sets of probability sets, J. Tables A2.1 and A2.2 report typical results. In the first panel, J consists of all probabilities less than 0.5. Unfortunately, our data sets are too small to distinguish the two models of densities. In neither case, the futures-implied densities, nor the options-implied densities, were the data able to reject the density as having generated them. This was true of all the probability sets we investigated.

This was largely the result of two qualities of our data. First, the data sets were small: there were only 14 independent outcomes. Second, this was a period of relative stability, in which the outcomes of the FOMC were fairly well known in advance. Most of the meetings placed a fairly high probability on one action (often "no change"). As a result, distinguishing the two forms of densities relies on distinguishing two assessments of low-probability events, an exercise that typically requires large data sets.

Table A2.1

P-values for Test of Density, J is all Probabilities $\in(0,.5)$

Forecast Horizon	# Observations	Options Density p-value	Futures Density p-value
8	13	0.2071	0.3288
14	14	0.1280	0.3542
21	14	0.7171	0.3851
35	14	0.3354	0.6842
41	13	0.3540	0.4459

Table A2.2

P-values for Test of Density, J is all Probabilities $\in(0,.25)$

Forecast Horizon	# Observations	Options Density p-value	Futures Density p-value
8	13	0.3727	0.6333
14	14	0.2295	0.6123
21	14	0.1415	0.3734
35	14	0.1893	0.6184
41	13	0.5378	0.6176

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Table 1

Descriptive Statistics for Single FOMC Estimation, by Contract*

Contract Month	May	June	July	Aug.	Sept.	Dec.	Feb.	Mar.	Apr.	May	Jul.	Aug.	Sep.	Oct.
Contract Year	2003	2003	2003	2003	2003	2003	2004	2004	2004	2004	2004	2004	2004	2004
FOMC Meeting Predicted	5/6/2003	6/25/2003	6/25/2003	8/12/2003	9/16/2003	12/9/2003	1/28/2004	3/16/2004	3/16/2004	5/4/2004	6/30/2004	8/10/2004	9/21/2004	9/21/2004
Target Rate Before Mtg.	1.25	1.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.25	1.50	1.50
Target Rate After Mtg.	1.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.25	1.50	1.75	1.75
Days	33	32	35	33	17	28	33	33	33	34	39	28	28	28
Number of Options	263	352	499	429	204	392	363	495	456	442	658	616	840	368
Fraction of Calls	0.350	0.364	0.355	0.462	0.333	0.429	0.545	0.400	0.434	0.462	0.634	0.545	0.433	0.457
Options Per Day														
Minimum	6	11	8	13	12	14	11	15	13	13	14	22	30	12
Maximum	10	11	17	13	12	14	11	15	14	13	18	22	30	14
Strike Price														
Minimum	0.7500	0.6250	0.6250	0.6875	0.5000	0.2500	0.8750	0.7500	0.6250	0.7500	0.8750	1.0000	0.7500	1.0000
Maximum	1.2500	1.3750	1.2500	1.1875	1.3750	1.5000	1.3125	1.5000	1.7500	1.2500	1.6250	1.8750	2.0000	2.0000
Days Until Maturity														
Minimum	26	11	38	19	27	24	32	17	47	26	32	23	11	40
Maximum	74	56	87	66	50	65	81	64	94	74	88	63	52	81
Futures Price														
Average	1.168	1.201	1.007	0.987	1.006	1.008	1.008	1.006	1.005	1.012	1.244	1.432	1.570	1.711
Minimum	1.090	1.165	0.835	0.955	1.000	1.005	1.000	1.005	1.000	1.005	1.120	1.420	1.560	1.670
Maximum	1.215	1.220	1.115	1.005	1.010	1.010	1.020	1.010	1.020	1.020	1.330	1.470	1.585	1.745

* The October 2003, November 2003, and January 2004 contracts never had a day with 5 or more options that had prices above the minimum of one-quarter basis point (.0025)
The June 2004 contract was not used since the second day of the June FOMC meeting was held on the last day of the month.

Table 2

Results for Single FOMC Estimation, by Contract*

Contract Month	May	June	July	Aug.	Sept.	Dec.	Feb.	Mar.	Apr.	May	Jul.	Aug.	Sep.	Oct.
Contract Year	2003	2003	2003	2003	2003	2003	2004	2004	2004	2004	2004	2004	2004	2004
FOMC Meeting Predicted	5/6/2003	6/25/2003	6/25/2003	8/12/2003	9/16/2003	12/9/2003	1/28/2004	3/16/2004	3/16/2004	5/4/2004	6/30/2004	8/10/2004	9/21/2004	9/21/2004
Days (PDFs estimated)	33	32	35	33	17	28	33	33	33	34	39	28	28	28
Unrestricted Estimation														
R-squared														
Average	0.9996	0.9981	0.9997	0.9995	0.9988	0.9993	0.9995	0.9999	0.9998	0.9995	0.9996	0.9999	0.9999	0.9997
Standard Deviation	0.0006	0.0036	0.0003	0.0002	0.0001	0.0003	0.0007	0.0000	0.0002	0.0004	0.0002	0.0001	0.0000	0.0003
Futures Price	(Actual - Predicted, in bp)													
Average	-0.759	-0.608	-0.172	-0.243	0.008	0.764	0.072	-0.509	-0.330	-0.136	-1.496	-0.075	-0.328	0.097
Standard Deviation	3.153	0.487	0.899	0.138	0.478	1.424	1.179	0.221	0.573	0.257	2.054	0.229	0.024	1.038
Minimum	-14.803	-2.750	-2.658	-0.397	-0.276	-1.093	-3.162	-1.097	-3.200	-0.799	-6.454	-0.855	-0.366	-3.105
Maximum	6.766	-0.234	1.567	0.083	1.734	3.846	2.000	-0.199	0.247	0.468	1.881	0.257	-0.287	1.424
Restricted Estimation														
R-squared														
Average	0.9994	0.9976	0.9997	0.9995	0.9988	0.9991	0.9994	0.9999	0.9998	0.9995	0.9995	0.9999	0.9999	0.9996
Standard Deviation	0.0009	0.0047	0.0003	0.0002	0.0001	0.0005	0.0007	0.0000	0.0002	0.0004	0.0004	0.0001	0.0000	0.0003
Futures Price	(Actual - Predicted, in bp)													
Average	-0.055	-0.330	0.019	0.047	0.045	0.040	-0.076	0.043	0.049	0.045	-0.029	-0.062	-0.017	-0.004
Standard Deviation	0.143	0.269	0.061	0.028	0.195	0.104	0.111	0.039	0.061	0.060	0.116	0.044	0.013	0.070
Minimum	-0.534	-1.510	-0.139	-0.004	-0.065	-0.153	-0.350	-0.051	-0.153	-0.156	-0.362	-0.183	-0.060	-0.316
Maximum	0.260	-0.065	0.145	0.156	0.435	0.240	0.054	0.116	0.188	0.177	0.253	0.036	0.002	0.055

* The October 2003, November 2003, and January 2004 contracts never had a day with 5 or more options that had prices above the minimum of one-quarter basis point (.0025)
The June 2004 contract was not used since the second day of the June FOMC meeting was held on the last day of the month.

Table 3 Joint FOMC Estimation Prices from July and August 2003 contracts on May 27, 2003 (Standard Errors in Parentheses)			
Jun 2003 FOMC Outcome	Aug 2003 FOMC Outcome	Unrestricted Probability	Restricted Probability
1.25		0.52100 (0.0066)	0.51460
1.00		0.27121 (0.0124)	0.26559 (0.0096)
0.75		0.21813 (0.0047)	0.21981 (0.0046)
	Sum	**1.01034**	**1.00000**
1.25	1.25	0.52146 (0.0135)	0.50422
1.25	1.00	-0.05652 (0.0437)	0.01038 (0.0136)
1.00	1.00	0.25708 (0.0391)	0.18775
1.00	0.75	0.00000 (0.0522)	0.02504 (0.0497)
1.00	0.50	0.04923 (0.0645)	0.05280 (0.0319)
0.75	0.75	0.16045 (0.0661)	0.14983
0.75	0.50	0.07111 (0.0250)	0.06997 (0.0202)
	Sum	**1.00281**	**1.00000**

Table 4
Comparison of Probabilities Estimated from Options Prices with Probabilities Recovered From Futures Prices

Contract (Number of Observations)	Probability	Mean Difference (percentage points)	Standard Deviation (percentage points)	t-Statistic	p-Value
May 2003 (33)	π^L	-22.9329	2.9568	-7.76	<.0001
	π^H	9.6549	1.5631	6.18	<.0001
June 2003 (32)	π^L	-54.6947	7.9196	-6.91	<.0001
	π^H	24.9721	3.5612	7.01	<.0001
July 2003 (35)	π^L	-23.4611	4.8615	-4.83	<.0001
	π^H	4.7272	4.6035	1.03	0.3117
August 2003 (33)	π^L	-0.0031	0.4476	-0.01	0.9946
	π^H	-4.0986	0.6270	-6.54	<.0001
September 2003 (17)	π^L	-7.1489	2.2768	-3.14	0.0063
	π^H	-4.0696	2.2594	-1.80	0.0905
December 2003 (28)	π^L	-5.6729	0.6719	-8.44	<.0001
	π^H	7.7840	0.7155	10.88	<.0001
February 2004 (33)	π^L	-1.7061	0.5311	-3.21	0.003
	π^H	-0.5293	0.4688	-1.13	0.2672
March 2004 (33)	π^L	-5.2308	0.5011	-10.44	<.0001
	π^H	2.8385	0.4094	6.93	<.0001
April 2004 (33)	π^L	-1.1455	0.3497	-3.28	0.0025
	π^H	-0.3708	0.6272	-0.59	0.5585
May 2004 (34)	π^L	-1.4746	0.4965	-2.97	0.0055
	π^H	1.0461	0.2403	4.35	0.0001
July 2004 (39)	π^L	3.6716	1.1915	3.08	0.0038
	π^H	-11.8664	2.1051	-5.64	<.0001
August 2004 (28)	π^L	-5.3330	2.5685	-2.08	0.0475
	π^H	-0.4167	2.2163	-0.19	0.8523
September 2004 (28)	π^L	-3.6046	0.7648	-4.71	<.0001
	π^H	6.2295	1.2468	5.00	<.0001
October 2004 (28)	π^L	2.4286	0.2789	8.71	<.0001
	π^H	-2.2391	0.4200	-5.33	<.0001
All (434)	π^L	-9.1349	1.0596	-8.62	<.0001
	π^H	2.3813	0.6764	3.52	0.0005

Table 5 Futures and Options Forecast Comparison			
Forecast Horizon in Days	Number of Contracts	Average Root Mean Square Error Across Contracts	
		Futures	Options
14	14	0.0059	0.0256
21	14	0.0058	0.0311
35	14	0.0107	0.0405

Table 6 – Descriptive Statistics for Variables Used In Fixed Effects Estimation 434 Observations				
Variable	Mean	Standard Deviation	Minimum	Maximum
$\pi_{i,t}^{A}$, the ex ante probability associated with the actual target rate chosen at the upcoming FOMC meeting	0.7873	0.2136	0.0630	1.1074
CPI Release	0.7005	0.6431	0	2
Employment Release	0.8065	0.6407	0	2
Economic Testimony	0.4401	0.6134	0	2
Economic Commentary	0.2673	0.5153	0	2
Days Until FOMC Mtg.	24.9747	13.9900	1	57
Considerable Period*CPI Interaction	0.0783	0.2857	0	2
Considerable Period*Employment Interaction	0.1452	0.4017	0	2
Considerable Period*Economic Commentary Interaction	0.0576	0.2333	0	1

Table 7 – Fixed Effects OLS Estimation Dependent Variable $\pi_{i,t}^{A}$, the ex ante probability associated with the actual target rate chosen at the upcoming FOMC meeting			
Lagged Probability			0.5735 (14.55)
CPI Release	0.0470 (3.11)	0.0565 (3.85)	0.0296 (2.36)
Employment Release	0.0410 (2.72)	0.0463 (3.18)	0.0333 (2.65)
Economic Testimony	-0.0340 (-2.62)	-0.0129 (-0.99)	-0.0183 (-1.70)
Economic Commentary	0.0996 (5.81)	0.0554 (3.03)	0.0526 (3.58)
Days Until FOMC Mtg.	-0.0029 (-3.09)	-0.0072 (-6.14)	-0.0005 (-0.60)
Days Until FOMC Mtg*Initial π_{i}^{A}		0.0077 (5.71)	
Considerable Period*CPI Interaction	-0.0466 (-1.49)	-0.0291 (-0.96)	-0.0199 (-0.77)
Considerable Period*Employment Interaction	-0.0704 (-2.73)	-0.0436 (-1.72)	-0.0382 (-1.73)
Considerable Period*Economic Commentary Interaction	-0.0994 (-2.67)	-0.0500 (-1.36)	-0.0523 (-1.68)
Number of Observations	434	434	420

t-statistics shown in parentheses

Figure 1
Average Daily Volume, All Contracts, Federal Funds Futures

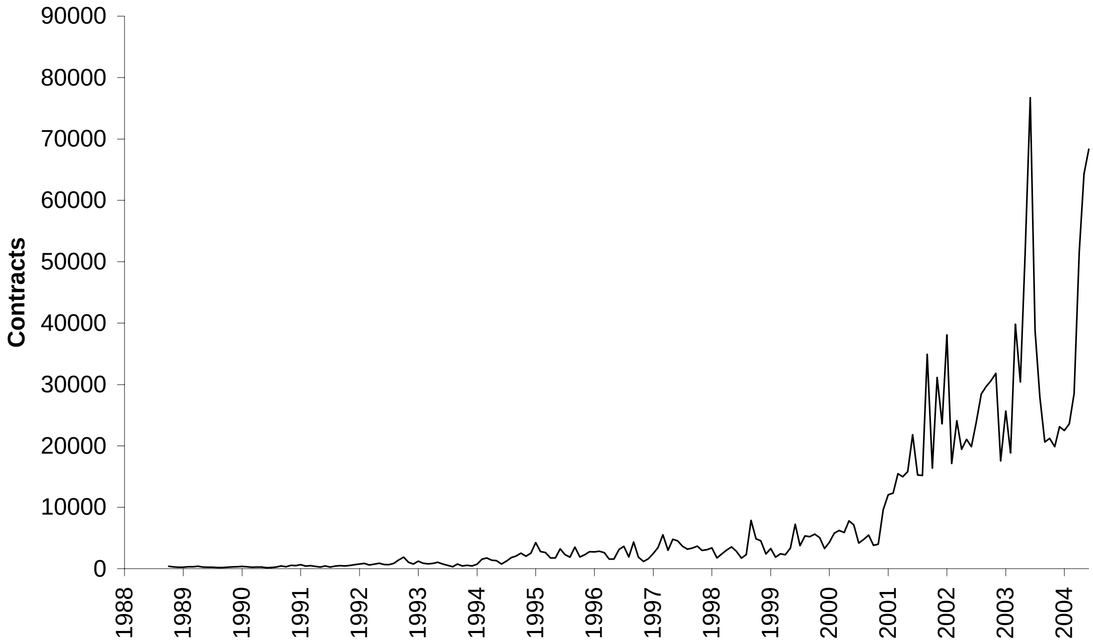


Figure 2
Daily Volume, All Contracts, Options on Federal Funds Futures

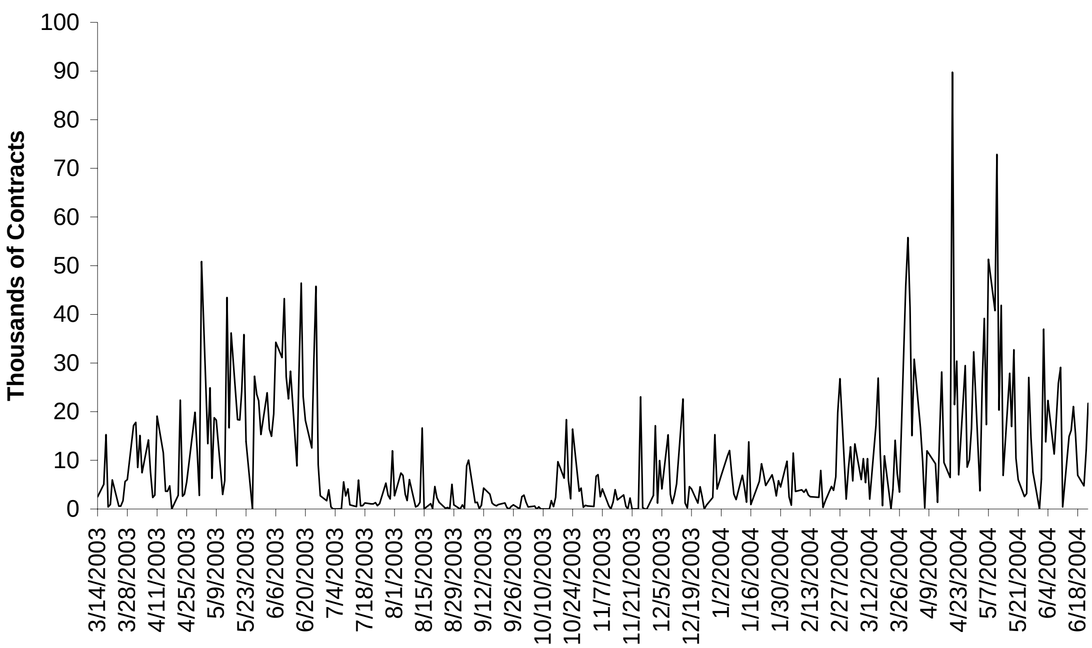


Figure 3
June 25, 2003 FOMC Meeting Target Rate Outcomes
(Based on May 27, 2003 options prices for the July 2003 contract)

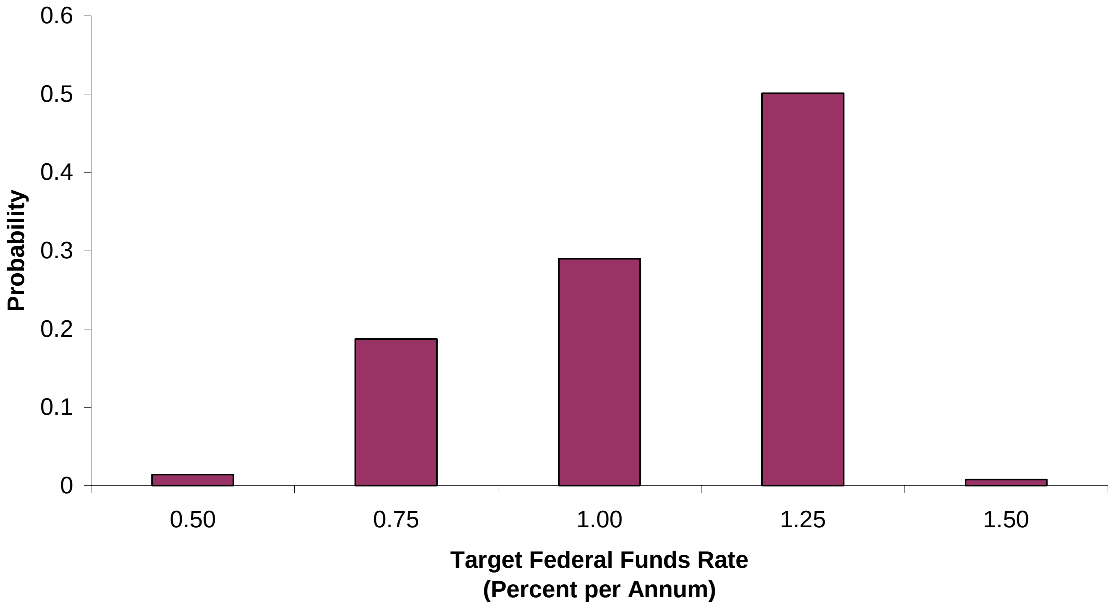


Figure 4
Probabilities for Target Rate Changes at the June 25, 2003 FOMC Meeting
(Based on Option Prices from the July 2003 Contract)

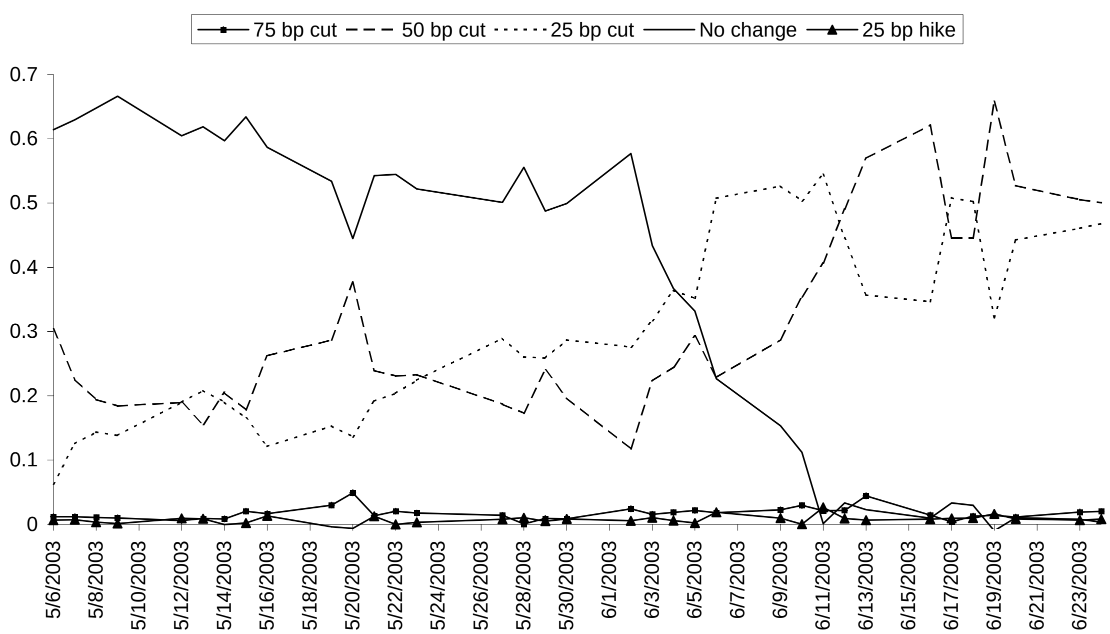


Figure 5a
June 25, 2003 FOMC Meeting Target Rate Outcomes
Joint Estimation with August 12, 2003 FOMC Meeting
(Based on May 27, 2003 options prices for the July and August 2003 contracts)

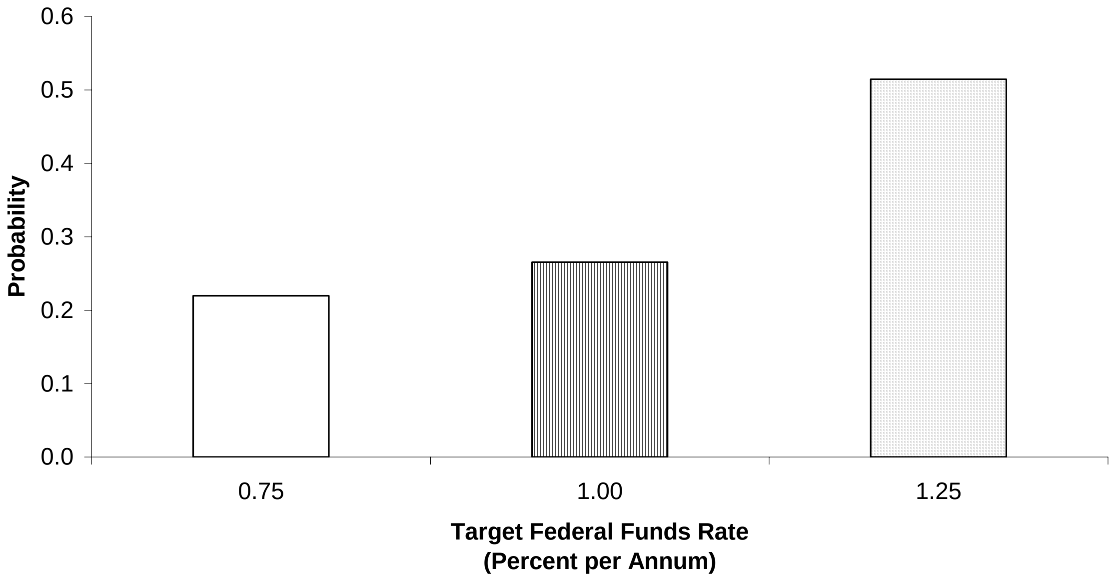


Figure 5b
August 12, 2003 FOMC Meeting Target Rate Outcomes
Joint Estimation with June 25, 2003 FOMC Meeting
(Based on May 27, 2003 options prices for the July and August 2003 contracts)

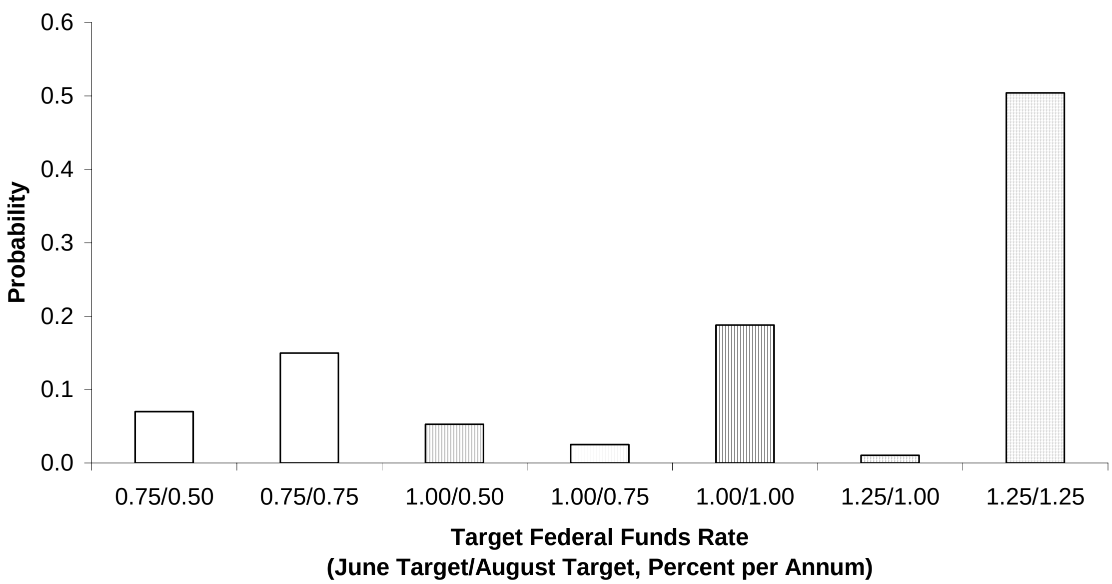


Figure 6
Probabilities for Target Rate Changes at the June 30, 2004 FOMC Meeting
(Based on Option Prices from the July 2004 Contract)

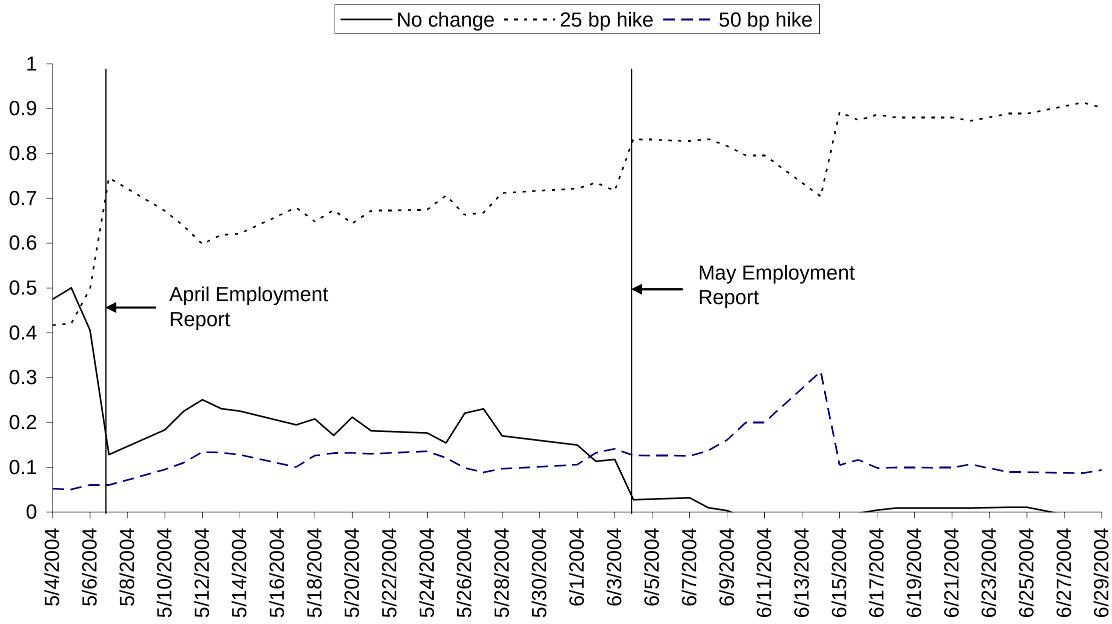
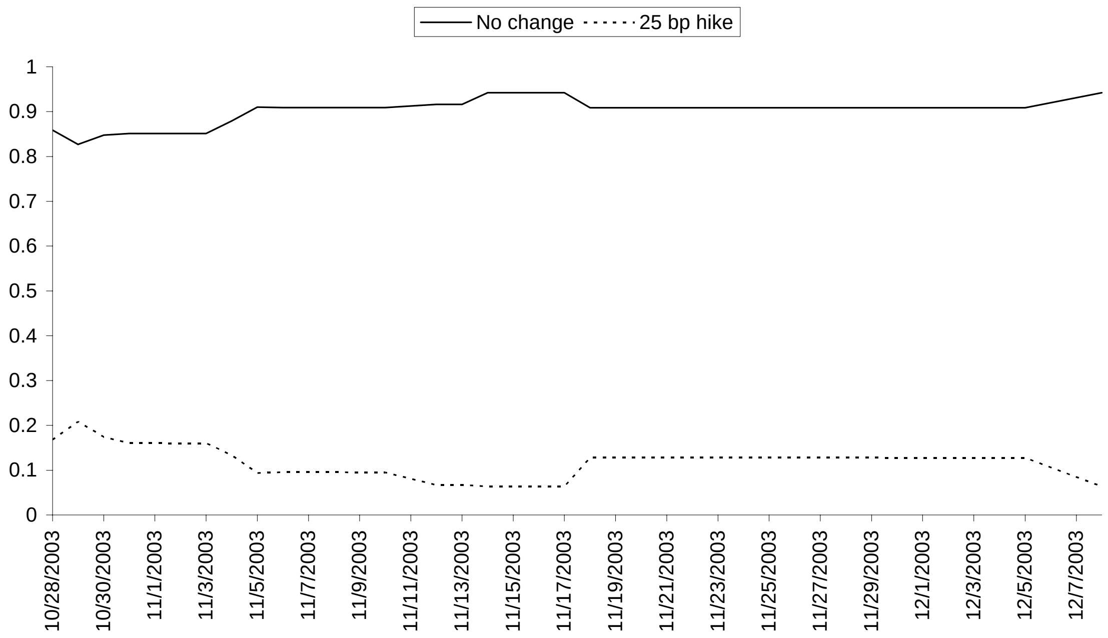


Figure 7
Probabilities for Target Rate Changes at the Dec. 14, 2003 FOMC Meeting
(Based on Option Prices from the Dec. 2004 Contract)



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