Volatility Forecasting in the US Money Market

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Abstract

This paper investigates the information content of implied volatility in the Eurodollar futures market. We find implied volatility is a biased estimator of realized volatility for standard options, but outperforms those based on historical yield changes. In the first use of midcurve options, we find implied volatility is an unbiased and efficient estimator for future realized volatility. We create a trading strategy to exploit the bias in standard options. The strategy loses money even without transactions costs.

Volatility Forecasting in the US Money Market

Volatility is an important part of modern finance. It is the key input in option pricing, value-at-risk models, and portfolio optimization. All of these need an estimate of *future* volatility over some horizon. The question is, “Which method of estimating future volatility is best?”

Over the past 15 years a growing body of research tests the forecast ability of different volatility measures. The ideal input would be unbiased and encompass all current information. Those based on historical returns, including the GARCH class, assume the future will look like the past. An alternative measure is the volatility implied in option prices. This implied volatility (IV) is the volatility input that sets the model price equal to the market price. It is an estimate of the underlying asset’s volatility over the remaining life of the option.

This paper investigates the accuracy of volatility forecasts from options on Eurodollar futures. Although this is an important market, there has been surprisingly little work in this area. Using standard options we find IV is a biased, but efficient forecast of future volatility. This is the first use of midcurve options in the literature; we find that these options generate unbiased and efficient forecasts of future volatility. A simple trading strategy designed to exploit the IV bias in standard options is unprofitable.

Related Literature

The literature shows IV is an efficient, but biased estimator of future volatility. This work has focused mainly on equities options, namely the S&P 100 and S&P 500 options. Canina and Figlewski (1993) find implied volatility is a poor estimate of realized volatility and a naïve historical volatility (HV) estimate dominates.

Conversely, Day and Lewis (1992), Fleming (1998), and Ederington and Guan (2002) find implied is better than historical. Ederington and Guan and Fleming develop trading strategies to exploit the bias. Fleming earns consistent profits before transactions costs. Ederington and Guan earn steady profits for most periods, but occasionally have large losses.

Jorion (1995) investigates volatility forecasting in the foreign exchange futures markets. Using Japanese yen, Swiss franc and German deutsche mark futures, he finds IV overestimates realized volatility, but is a better forecaster than HV.

In interest rate markets, Oldfield (2002) finds that the IV from options on New Zealand Bank Accepted Bills outperforms several measures of HV, but IV is still biased. IV exceeds actual volatility 83% of the time. After correcting for the upward bias, he finds his model forecasts volatility very well. Using Australian Bank Accepted Bills, Kelly and Chaput (2006) find implied volatility is an upwardly biased, but efficient forecaster of future volatility using overlapping and non-overlapping periods.

Szakmary et al (2004) test the efficiency of IV in 35 futures markets, including Eurodollars, and find IV is best in 34 of the markets. Similar to the present paper, they use Figlewski's (1999) "OUCH"[1] estimator to compute the HV. With respect to Eurodollars they find IV a biased, but efficient estimator of RV.

In a study closely aligned with the current one, Neely (2005) finds IV is a biased predictor of futures volatility in the Eurodollar futures market. There is a problem with Neely's study: he uses the volatility of the underlying futures contract while the market uses the implied underlying interest rate (See Burghardt (2003)). The Eurodollar futures price is based on the IMM Index of $F = 100 - R$ where F is

[1] OUCH is an acronym for Optimized Unconditional Conditional Heteroskedaticity.

the futures price and R is the interest rate. By using the wrong underlying asset in his estimate, his conclusions need to be interpreted with caution.

Implied Volatility as a Forecast of Future Volatility

There are several potential sources of the bias suggested in the literature with some proposals on how to mitigate them. These include: model misspecification, non-synchronous trading, transactions costs, a non-normal return distribution, and the existence of a volatility risk premium. Each of these will be discussed in turn.

Model misspecification arises when the researcher uses one pricing model while the market uses another. It is common to use the Black-Scholes (1973) or Black (1976) model for European options when the traded option is American. If there is an early exercise premium in the price, this will overstate the IV. Jorion (1995) estimates the amount of bias in foreign exchange options and finds it to be very small.[2] To reduce the error, one could use a pricing model for American options, such as the binomial model of Cox, Ross, and Rubinstein (1979) or Barone-Adesi and Whaley (1988).[3] This study uses Barone-Adesi and Whaley (1988) to account for the potential of early exercise.

Non-synchronous trading occurs when the option price(s) and underlying asset price are not observed at the same time, or when the markets close at different times and the closing prices are used. An example is the US equity market which closes at 3:00pm CT and the associated options market is open until 3:15pm CT. So any time lag induced by delayed or stale prices may lead to spurious results.

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[2] Whaley (1987) finds the early exercise premium to be small for at-the-money and out-of-the-money options. Deep in-the-money options can have a substantial premium. Because this and previous studies use at-the-money options, any bias should be small.
[3] One could use a trinomial model, but it does not lead to easy computation of the delta needed for hedging.

Using settlement prices of futures and options on futures reduces this problem greatly. Because the exchange uses settlement prices to establish marking-to-market payments and margin requirements, the prices need to reflect the market at closing time. First, they trade side-by-side during the day and close at the same time. This leads to no delay in prices. Second, the settlement procedure for options on futures places several requirements on the settlement prices. The futures must settle before the options to allow an accurate input. Each option's settlement price must be within the bid and ask prices at the close ($Bid \leq Settle \leq Ask$) and must obey put-call parity and several others rules.[4] This procedure generates prices that reflect current market conditions at the close. We use settlement prices in this study.

Transactions costs are an unavoidable part of trading. Anyone wishing to establish a position must pay them one way or another. The most transparent cost is the commission. Commissions have been falling over time, but still can be quite large. In equity markets, they may be pennies per share. In equity options, commissions are composed of a fixed and variable component, which can still be substantial. In futures markets, transactions costs are quoted on a round-trip basis and, even for retail investors, are usually less than one tick.[5]

A potentially larger cost, but harder to measure, is the bid ask spread. For equity and equity options, databases include the most current bid and ask prices. In futures markets, the databases record prices only if they differ from the previous one recorded. For active contracts the spread can be modeled as in Smith and Whaley

[4] These include ensuring prices are bounded current orders for combinations and spreads and they obey arbitrage bounds like those established in Merton (1973).

[5] In the early 1990s discount brokers offered $15 per round-trip. A perusal of commissions in May, 2007 shows discount brokers charging $7 per round-trip for retail clients. Institutions can negotiate lower rates. In the early 2000s a larger broker charged institutions $7.50 round-trip. Half is paid at the opening of the position. The other half is charged when the position is offset, expires, or, in the case of options, exercised. If exercised, the fee was normally waived and paid when the futures position terminated.

(1993). Though futures options are liquid, individual strikes may not trade frequently. Estimating the bid-ask spread for them is a challenge. [6]

The last two problems are more difficult to deal with. Option pricing models usually assume the return distribution of the underlying asset is normal. This assumption has been shown to be false for equities, indices, interest rates, currencies, and commodities. Assets exhibit too many large jumps in prices (usually down) than suggested by the normal distribution. These leptokurtotic distributions are much harder to model. By assuming an incorrect return generating process, the model may misprice options.[7]

The volatility risk premium arises because volatility is not constant. Asset markets tend to exhibit periods of high volatility and periods of quiet. Volatility also tends to increase more for negative shocks than for positive shocks. If these periods are correlated with systematic risk, then traders should be compensated for bearing this risk. Fleming (1998) tests for the volatility premium and finds no support. Bakshi and Kapadia (2004) estimate that the volatility risk premium increases the IV by two percentage points to help compensate option sellers for the risk of jumps in volatility.

This paper overcomes the first two problems by using a model for pricing American options and using settlement prices for the options and futures. Transactions costs, non-normal returns and the volatility risk premium may be present, but are not considered. The next section goes over some of the details of the Eurodollar contracts.

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[6] Even if an option trades, there may be no price in the trade record. When an option is part of a spread or combination, the exchange records the volume, but not the price assigned to the option.
[7] A model should not be assessed on its assumptions, but on its predictions.

Eurodollar Futures and Options

The three-month Eurodollar futures contact and its associated options are the most actively traded short-term interest rate products in the world (Burghardt, 2003). They trade on the International Monetary Market at the Chicago Mercantile Exchange. The futures have quarterly expirations up to ten years out. The options have quarterly expirations up to two years out. These options expire into the futures contract of the same maturity. Both the options and the futures expire on the same day. In addition there are short term options on longer dated futures. These "midcurve"[8] options expire in less than one year, but the underlying future has one or more years before its maturity. A third type of Eurodollar options are serial options. These are short maturity (less than three months) options that track the next expiring futures. For example, the January, 2007 and February, 2007 serial options are based on the March, 2007 futures. Similarly, the April, 2007 and May, 2007 follow the June, 2007 futures. The final type of options is serial midcurve options. These expire in non-quarterly months, but are priced on the next quarterly contract that matures in over one year. For example, the January, 2007 and February, 2007 serial one-year midcurve options track the March, 2008 futures contract. Table 1 shows the option maturities and their underlying futures available on 02 January, 2007.

The futures are based on the three-month LIBOR at maturity and are cash settled. Being based on LIBOR ties them to the forward rate agreement and swaps markets. The puts on Eurodollar futures are near equivalents to caplets and the calls floorlets.[9] This substitutability makes them excellent hedges and useful for arbitrage. See Burghardt (2003) for more details of the Eurodollar futures and options markets.

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[8] Nidcurve is a reference to the futures maturity being in the middle of the yield curve.
[9] Eurodollar options are American, while caps and floors are normally European.

Given the size of the market, it is surprising there is such little work assessing the forecasting of volatility. As mentioned earlier Szakmary et al (2003) and Neely (2005) are the only papers to address this issue. This paper aims to build on their work.

The Types and Nature of Volatilities

There are several types of volatilities that are of interest: realized (or future[10]), historical, and implied. Each of these measures a different thing. Realized volatility is the standard deviation of daily returns after some measurement date, equation (1). It may also be the square root of the sum of squared price returns, equation (2) .

$$\sigma_{RV}(t,T) = \sqrt{\frac{252}{T-t}\sum_{i=t}^{T}\left(r_i - \bar{r}\right)^2} \quad (1)$$

$$\sigma_{RV}(t,T) = \sqrt{\frac{252}{T-t}\sum_{i=t}^{T} r_i^2} \quad (2)$$

$$r_i = \ln\left(\frac{100-F_i}{100-F_{i-1}}\right) \quad (3)$$

σ_{RV} is the realized volatility from t to T. r_i is the return on date i. $\bar{r}$ is the mean return. This return is that of the (implied) futures (interest) rate, not the futures price used by Neely (2005).

Historical volatility is usually the daily standard deviation of returns or the square root of the sum of squared price returns, equations (4) and (5). It may also take more complex forms such as an exponentially weighted moving average or a GARCH model. The key facet is that historical volatility is based on returns *before* the measurement date.

[10] In a recent paper Andersen et al (2003) use the term "realized volatility" to be the standard deviation of returns taken over very short intervals. Their measure is closer in spirit to continuous time. This paper uses the traditional definition of the standard deviation of daily returns.

$$\sigma_{HV}(t-k,t)=\sqrt{\frac{252}{k}\sum_{i=t-k}^{t}\left(r_i-\bar{r}\right)^2} \tag{4}$$

$$\sigma_{HV}(t-k,t)=\sqrt{\frac{252}{k}\sum_{i=t-k}^{t}r_i^2} \tag{5}$$

Here σ_{HV} is the historical volatility from $t-k$ to t.

Implied volatility is the volatility that makes the model's price equal to the observed market price. Because options are traded assets and the risk of asset price changes can be hedged away, many believe the IV is the market's consensus forecast of volatility over the remainder of the option's life. If someone believed the IV was too low, she would buy options and delta hedge until the price reflected her opinion. Similarly if the IV was too high, people would sell options until IV was in equilibrium. This trading should make IV reflect the market's consensus forecast. In an efficient market this forecast would be unbiased and contain all available information.

Testing for Unbiasedness and Efficiency

Unbiased forecasting methods go back to Theil (1961). The model involves regressing realized volatility on some forecast estimate. The null hypothesis is the estimate is unbiased given information available. This is equivalent of $\alpha = 0$ and $\beta = 1$ in equation (6). The alternative hypothesis is the estimate is biased with $\alpha \neq 0$ and/or $\beta \neq 1$.

$$\sigma_{RV}(t,T)=\alpha+\beta\sigma_{FV}(\Phi_t)+\varepsilon_t \tag{6}$$

Where $\sigma_{FV}(\Phi_t)$ is the forecast of $\sigma_{RV}(t,T)$ at time t, given the information available at Φ_t. We use the implied volatility and the simple standard deviation of returns.

To determine if IV includes all information available at the time of the forecast, an encompassing regression is run including IV and a measure of HV. The null hypothesis is IV is efficient and unbiased. This is equivalent to $\alpha = 0$, $\beta_{IV} = 1$, and $\beta_{HV} = 0$ in equation (7).

$$\sigma_{RV}(t,T) = \alpha + \beta_{IV}\sigma_{IV}(\Phi_t) + \beta_{HV}\sigma_{HV}(\Phi_t) + \varepsilon_t \qquad (7)$$

Data

The data used are the daily settlement prices of Eurodollar futures, Eurodollar futures options and spot LIBOR. The futures and standard expiration options were acquired from the Commodity Research Board. Midcurve option prices were acquired from the Chicago Mercantile Exchange. The constant maturity Treasury yield is used as the risk-free rate.[11]

Several samples are used in this study. The full sample uses at-the-money volatilities computed each day for each available maturity. A second sample uses only the quarterly options with the shortest time to maturity with only one observation per maturiy. This creates datasets with non-overlapping observations and reduces the serial correlation. One month (21 trading days to maturity), two months (42 trading days), and three month (63 trading days) maturities will be used.[12] This is in line with studies of the equity and foreign exchange markets. The overlapping samples lead to correlation among the residuals because the realized and historical volatilities will contain return data from prior observations. This is accounted for by using Hansen's correction to adjust the standard errors to properly reflect serial correlation of varying lengths in the residuals of regressions (Hansen, 1982).

[11] The three month rate is used for all maturities less than 4.5 months. The six month rate is used for maturities between 4.5 and 11 months. The one-year rate is used for maturities of 11 to 18 months. All other maturities use the two-year CMT rate.
[12] The periods vary to ensure that there is no overlap and an option is available in each period.

To compute the IV the options with a strike price nearest the futures price will be chosen.[13] The IV will be computed using the settlement price of the straddle. This will average out some errors arising from price discreteness. The formulae used to compute the IV is Barone-Adesi and Whaley (1988, hereafter BAW) adapted to options on futures.

$$C_t = c_t + \left(\left(\frac{F^*}{q_2} \right) \left[1 - e^{-rt} N\left(d_1\left(F^* \right) \right) \right] \right) \left(\frac{F}{F^*} \right)^{q_2} \tag{8}$$

$$P_t = p_t + \left(\left(-\frac{F^{**}}{q_1} \right) \left[1 - e^{-rt} N\left(-d_1\left(F^{**} \right) \right) \right] \right) \left(\frac{F}{F^{**}} \right)^{q_1} \tag{9}$$

$$c_t\left(F_t, X, r, \sigma, T-t \right) = e^{-r(T-t)} \left[F_t * N\left(d_1 \right) - X * N\left(d_2 \right) \right] \tag{10}$$

$$P_t\left(F_t, X, r, \sigma, T-t \right) = e^{-r(T-t)} \left[X * N\left(-d_2 \right) - F_t * N\left(d_1 \right) \right] \tag{11}$$

$$d_1 = \frac{\ln\left(\frac{F_t}{X} \right) + \frac{\sigma^2 (T-t)}{2}}{\sigma \sqrt{(T-t)}} \tag{12}$$

$$d_2 = d_1 - \sigma \sqrt{(T-t)} \tag{13}$$

$$q_1 = \frac{1 - \sqrt{1 - 4\frac{M}{K}}}{2} \tag{14}$$

$$q_2 = \frac{1 + \sqrt{1 - 4\frac{M}{K}}}{2} \tag{15}$$

$$M = \frac{2r}{\sigma^2} \tag{16}$$

$$K = 1 - e^{-rt} \tag{17}$$

[13] Chaput and Ederington (2003) find vega is maximized slightly above the current futures price. Due to price discreteness, this is rarely a traded strike, but close to the at-the-money strike. When it is not the ATM strike, Chaput and Ederington find traders still chose the ATM straddle with little loss of vega.

Where C_t is the American call price at time t, P_t is the American put price at time t, c_t is the European put price, p_t is the European put price, F_t is the futures price at t, X is the exercise price, r is the risk-free rate, $(T-t)$ is the time to maturity of the option, and σ is the volatility of the log changes in the implied futures rate. The BAW model is used because it is an accurate approximation for American style options[14].

The historical volatilities will be computed using equations (4) and (5). Following Figlewski's (1999) OUCH estimator, the estimation period equals the forecast period, as measured in trading days. Figlewski compares this to several other measures of historical volatility and finds it is superior. It has intuitive appeal because the amount of information used is equal to that required to calculate the RV. We now look at some of the characteristics of the data.

Summary Statistics

Table II presents summary statistics for RV, IV and IV of the standard options. Panel A contains the full sample. We see all volatility measures are of the same order of magnitude and have similar standard deviations. The mean and median values for RV are 19.19% and 15.72%. IV is higher with values of 20.79% and 17.97%. Average HV is 21.53% and its median is 18.28%. The final two columns have the pair-wise differences between IV and RV and HV and RV. Both IV and HV significantly overestimate future RV by 1.54% and 2.35% respectively.

Panels B through D contain the statistics for the non-overlapping periods. Again IV is not a perfect forecaster of RV. Note that all measures of volatility decrease with maturity, with RV falling the fastest and RV the slowest. This leads to

[14] The Newton-Raphson method is used to get the IV using Black (1976) for the equivalent European option. The bisection method using the European IV as a seed is used to get the American IV.

increasing differences between RV and IV and HV, as seen in the last two columns. In summary IV and RV significantly overestimate RV in all maturity groupings for standard options.

Table III has the sample characteristics for the one-year midcurve options. Notice that the measures of central tendency are all higher than for the standard options. The mean for RV and IV for all samples is approximately 29% with medians around 20%. HV means are between 26% and 28% and the median is about 19.5%. None of the differences between IV and RV are significantly different from zero and all are positive. Only the full sample has a significant difference for HV and RV, where all mean differences are negative. For the one-year midcurve options, it appears both HV and IV are good forecasters of RV. The next section will test this more stringently.

Table IV has the sample statistics for the two-year midcurve options. As with the one-year midcurve options, all means and medians are higher than for standard options. The means are less than the corresponding means for the one-years and the medians are about the same. As with the other options, IV exceeds RV on average, with only the full sample significantly so. The differences between HV and RV are mixed with only the full sample being significant and negative.

Figure 1 plots the term structure of volatility for the three option types. We find the term structure for the standard options is monotonically upward sloping. This is in contrast to the usual inverted term structure found in equities and foreign exchange. One possible reason for this is there is usually little uncertainty for short-term interest rates, unless the central bank is changing rates.

The one-year midcurve options have a downward sloping term structure, while the two-years are roughly upward sloping. Both plot well above the corresponding points for the standard options. This is not unexpected given the data in Tables II, III, and IV.

Shorter maturity forward rates are less volatile than longer maturity rates over the near term. The standard options track forward rates that will occur in one year or less. One-year midcurves track rates that will occur in 12-24 months, while the two-year midcurves track rate that will arise in 24-36 months. It appears that interest rate uncertainty increases with maturity for two years out or so, then tapers off. This could imply that interest rates are mean reverting, but we will not investigate this here.

The preceding showed that FV-RV is significantly larger than zero for standard options, but not for midcurve options. The next section presents the results of the regressions to see if this overestimation is significant. We also explore whether IV is informationally efficient.

Regression Results

The results of the bias regressions for standard options are in Table IV. We see the null hypothesis of $\beta = 1$ is rejected in all the restricted samples for HV and RV. In all cases for HV, the intercept is different from zero and the slope coefficient is different from one. The full sample (Panel A) finds the coefficient for IV is closer to unity than all other arrangements, has an intercept significantly different from zero, and has the highest adjusted R^2. The betas for IV range from 0.6861 for three months to 0.8812 in the full sample. In comparison the betas for HV are between 0.4490 and 0.5939. In all cases the coefficient is greater in the IV regressions. These results show all measures of forecasted future volatility are upwardly biased. These findings are not unexpected given the statistics in Table II. They also are in agreement with the findings in Table II, where HV > IV > RV. The question now turns to whether one measure is more efficient than the others.

The last column of Table V contains the parameter estimates for the encompassing regressions. The coefficient for IV is indistinguishable from unity in all cases and, importantly, the coefficient for HV is not different from zero in the sub-samples and significantly *less* than zero in the full sample. The R^2s for the encompassing regressions are marginally different from those with IV only. The regressions show IV contains all available information about future volatility. The results are in line with Szakmary et al (2004) for futures markets.

We find HV and IV generate biased forecasts of RV for rate volatility in Eurodollar futures. IV is found to be a superior, but not perfect, forecast of RV. The results show that IV contains all the information that the HV measures do. We next test how well midcurve options forecast future volatility.

Given the statistics in Table III and IV, we expect IV and HV to provide good forecasts of RV for midcurve options. We look at the one-year midcurve options first and two-year midcurve options last.

The results for the more liquid one-year midcurve options are presented in Table VI. We find a stark contrast between the forecast ability of the one-year midcurve options and the standard options. For the non-overlapping periods we find that we can not reject the null hypothesis that IV is an unbiased forecast of future RV for both one-year midcurve options. The intercepts are all zero, except in the one month non-overlapping sample, and the slope coefficients are not different from unity. With R^2s between 0.7631 and 0.850, we find a good deal of the variation is explained.

Similarly we find that HV is also an unbiased forecast of RV in the non-overlapping samples. The coefficients are less than those for IV and the R^2s are smaller. Thus HV is also a good predictor. This is not surprising given the numbers in Table III. The encompassing regressions will help determine which is more informative. The last column of Table VI contains the results for the encompassing regressions. For the entire sample we find slope of IV is significantly less than one and the slope of HV has dropped greatly. Thus, IV contains more information. For the sub-samples all intercepts and the slope of HV are indistinguishable from zero. The coefficients for IV are all different from one, but not statistically so. These results show IV contains all information the HV contains with respect to future RV.

Table VII contains the results for the two-year midcurve options. Only in the full sample for the one-year midcurve options do we find $\beta \neq 1$ at any reasonable level of significance at 0.9307. In the non-overlapping periods, we find the intercept is zero and the slope coefficient not different from one. The results are generally the same for HV. In all cases, the coefficients are less than those for IV and the R^2s are smaller. Again, HV is also a good predictor.

The encompassing regressions for efficiency show that coefficient for IV is indistinguishable from one in every case, bar the full sample. Importantly, the slope for HV is zero in all cases, as is the intercept. IV contains all information about RV for the two-year midcurve options.

This section has found contrasting results. For the standard options on Eurodollar futures, we find IV to be a biased, but informationally efficient estimate of future volatility. For the one- and two-year midcurve options we find both IV and HV to be unbiased forecasts of future RV. When compared to each other, we find IV contains more information and HV is a poor forecaster. The next section develops a trading strategy to exploit the biased volatility forecasts of IV for the standard options on Eurodollar futures.

Profitability Tests

In the spirit of Whaley (1987) and Fleming (1998) we develop a trading strategy to exploit the biased IV. If IV is an upwardly biased forecast of RV, we should be able to sell the overpriced options and earn excess returns. We create a portfolio by selling options and evaluating there profits at maturity. More specifically, each day we sell the nearest to expiration, at-the-money straddle. For the one month sample, we have 21 straddles open on most days. The second strategy involves writing straddles daily and delta hedging. The portfolio is rebalanced daily by trading futures to bring it back to neutrality. Daily profits are computed and the portfolio is held to maturity. If profits are available in these strategies, markets may be inefficient or they may exhibit imperfections.

The portfolios are constructed as follow. Each day an at-the-money straddle is sold for the nearest maturity in the quarterly cycle. All portfolios are held to maturity.[15] The proceeds are held in an account that earns the spot constant maturity Treasury rate until maturity. For the hedged portfolio $-\frac{\partial C}{\partial F}-\frac{\partial P}{\partial F}$ futures contracts will be acquired upon initiation. At the end of the each succeeding day, a new delta will be computed and the hedge readjusted. Total profits are

$$\Pi = \left(C_t + P_t\right) * \left(1 + r_t\right)^{(T-t)} - \left|F_T - X\right| + \sum_{k=t}^{T-1}\left(-\frac{\partial C}{\partial F} - \frac{\partial P}{\partial F}\right)_k * \Delta F_k \qquad (18)$$

The first term on the right hand side is the future value at maturity of the premium received. The second term is the payoff to the straddle. The final term is

[15] This is supported by Chaput and Ederington (2005) who find very few straddle trades are offset before maturity.

the total gains or losses from the rebalanced futures hedge. This is equivalent to Whaley's (1987) sold option portfolio.

Table VIII has the results of the profitability tests. The average delta is quite small as expected because at-the-money calls and puts have deltas of approximately the same magnitude, but of opposite signs. The unhedged portfolio is monotonic in its losses as maturity increases. For the three month period, we find average losses of 2.1329bp ($53.3225) decreasing to 1.6812bp ($42.03) for the two-month sample and 0.6314bp ($15.785) for the one month sample. Thus even before transactions costs, these trades are unprofitable.

Similarly, the hedged portfolios all make losses and are again significantly less than zero. As before, the longer holding periods generate greater losses. Taken together it seems the options on Eurodollar futures markets are efficient. Though IV is a biased forecast of RV, we can not exploit this with any consistency in a naïve trading strategy. Potentially more complex strategies, such as creating vega or gamma neutral portfolios, are unlikely to help due to the existence of transactions costs.

Summary and Conclusions

This paper looks at the information content of options on Eurodollar futures. We find the implied volatility is a biased estimator of future volatility for the standard options. Compared to estimates based on historical returns, implied volatility is found to be superior. For the midcurve options we find IV to be an unbiased and efficient forecast of future RV. This result not only contrasts with our findings for the standard options, but also with most other research. Thus we find the midcurve option market to be efficient.

A simple trading strategy was used to determine if profits can be earned from trading on the biased implied volatility in the standard options. We find that in all sample periods the short straddle strategy generates losses, even when including interest earned on the premium and with daily rebalancing to delta neutrality. We conclude that even though IV may be a biased forecast of RV, the options on Eurodollar futures market is efficient.

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Table 1. Eurodollar Options Expirations and the Underlying Futures

This table presents the menu of options available in the options on Eurodollar futures market on 02 January, 2007. There are eight quarterly maturities that expire with their underlying futures. There are also two serial expirations (Jan-07 and Feb-07) that track the Mar-07 futures. These are denoted with X. The other options are midcurve options that mature in 2007, but the underlying futures mature in later years. There are two serial midcurve options that track the Mar-07 futures. Midcurve options are noted with M.

	Underlying Futures Contract Expiration															
Option Expiration	**Mar-07**	**Jun-07**	**Sep-07**	**Dec-07**	**Mar-08**	**Jun-08**	**Sep-08**	**Dec-08**	**Mar-09**	**Jun-09**	**Sep-09**	**Dec-09**	**Mar-11**	**Jun-11**	**Sep-11**	**Dec-11**
Jan-07	X				M											
Feb-07	X				M											
Mar-07	X				M				M				M			
Jun-07		X				M				M				M		
Sep-07			X				M				M				M	
Dec-07				X				M				M				M
Mar-08					X											
Jun-08						X										
Sep-08							X									
Dec-08								X								

Table II. Volatility Measure Descriptive Statistics - Standard Options

This table presents the mean, standard deviation, skewness and kurtosis for the various measures of volatility. RV-IV and RV-HV are the differences between realized volatility and implied and historical volatility, respectively, in percent. * and ** represents significantly different from zero at the 5% and 1% level, respectively.

Panel A: Full Sample

	RV	IV	HV Ouch	IV - RV	HV - RV
μ	19.1876	20.7850	21.5335	1.5369 **	2.3459 **
σ	12.6171	11.4842	13.1529	7.6459	11.2562
Skewness	1.3550	1.4190	1.4953	-0.6416	-0.0577
Kurtosis	1.4305	1.9878	2.3020	3.3322	1.6538
25th	10.9085	13.4108	12.9140	-1.4584	-2.4757
Median	15.7226	17.9662	18.2811	2.4906	2.2707
75th	22.8563	24.1094	25.5926	5.7941	8.0171
N	37911	37732	37911	37732	37911

Panel B: Non-overlapping One Month

	RV	IV	HV Ouch	IV - RV	HV - RV
μ	10.4346	12.9777	13.2513	2.5431 **	2.8167 **
σ	7.4314	7.7890	9.1933	5.7134	8.4008
Skewness	1.4153	1.2874	1.7650	-0.0725	0.8982
Kurtosis	2.5087	1.7080	4.6473	0.9937	4.6490
25th	5.0555	7.2258	7.2371	-0.0022	-0.6683
Median	9.2831	11.1447	11.4944	2.3714	2.3754
75th	13.6462	15.8049	16.8859	5.5516	6.4623
N	85	85	85	85	85

Panel C: Non-overlapping Two Month

	RV	IV	HV Ouch	IV - RV	HV - RV
μ	12.4332	14.6603	17.7444	2.2271 **	5.3112 **
σ	7.7012	7.5922	10.4573	4.4787	8.1089
Skewness	1.3060	1.1396	1.5334	-1.2210	1.4785
Kurtosis	2.1980	1.6137	2.9156	6.8045	6.8900
25th	6.6062	8.3866	10.3732	2.2101	0.6875
Median	11.3817	13.7152	15.0403	2.3712	4.4963
75th	16.3159	18.3538	22.2492	4.6774	7.9861
N	84	84	84	84	84

Panel D: Non-overlapping Three Month

	RV	IV	HV Ouch	IV - RV	HV - RV
μ	13.8600	17.1222	21.0457	3.2621 **	7.1856 **
σ	8.1793	8.4966	11.7919	5.1076	9.0042
Skewness	1.0722	1.2072	1.2150	-0.6057	0.7748
Kurtosis	0.6778	1.5655	0.6191	2.0186	2.0381
25th	7.3396	10.8866	13.1378	1.1240	2.5643
Median	11.9138	16.1165	17.1844	3.3674	5.9963
75th	18.5224	19.8550	24.9600	6.0500	10.1661
N	83	83	83	83	83

Table III. Volatility Measure Descriptive Statistics - One-year Midcurve Options

This table presents the mean, standard deviation, skewness and kurtosis for the various measures of volatility. RV-IV and RV-HV are the differences between realized volatility and implied and historical volatility, respectively, in percent. * and ** represents significantly different from zero at the 5% and 1% level, respectively.

	RV	IV	HV Ouch	IV - RV	HV - RV
Panel A: Full Sample					
μ	29.0699	29.1177	25.9946	0.1565	-3.0753 **
σ	19.5283	17.1176	19.5024	9.4355	11.3580
Skewness	1.1794	1.2779	1.6231	-0.4813	-0.5907
Kurtosis	0.49089	0.6877	3.3369	2.9229	3.9780
25th	14.2673	16.25718	13.7922	-3.6553	-7.6812
Median	20.4818	21.6119	19.5024	1.9536	-0.1892
75th	41.1914	37.5045	33.7969	5.3640	3.6977
N	13561	13526	13561	13526	13591
Panel B: Non-overlapping One Month					
μ	28.7426	29.9030	28.7006	1.1604	-0.0420
σ	21.8967	19.5741	20.6445	8.3834	9.2870
Skewness	1.3259	1.2523	1.2498	-1.6922	-0.7234
Kurtosis	0.6720	0.3959	0.7305	4.6746	1.5490
25th	13.3260	15.9084	14.0790	-1.9828	-5.1071
Median	19.3064	19.8286	20.0855	2.4222	0.7713
75th	38.7812	41.8546	38.3455	6.9347	4.7077
N	40	40	40	40	40
Panel C: Non-overlapping Two Month					
μ	29.0193	29.9268	27.7044	0.9075	-1.3149
σ	20.7547	17.7645	19.1996	8.0708	8.8587
Skewness	1.2965	1.0559	1.2670	-1.7315	-1.5540
Kurtosis	0.7537	-0.3734	0.4394	3.8950	4.5980
25th	13.4804	15.9686	14.3525	-1.2513	-4.6367
Median	19.6227	21.7265	19.0944	1.7913	0.4589
75th	40.2943	40.4737	35.7333	4.9679	2.5477
N	40	40	40	40	40
Panel D: Non-overlapping Three Month					
μ	29.1342	29.7044	27.0779	0.5702	-2.0563
σ	20.1932	18.0377	17.8979	8.0511	11.0637
Skewness	1.2259	1.1632	1.2785	-1.7819	1.8767
Kurtosis	0.5451	0.0815	0.9084	5.8654	5.0944
25th	13.1295	15.3680	13.2997	-1.7680	-5.4681
Median	20.9128	23.1583	18.7407	1.6110	0.4734
75th	41.6369	38.2179	39.0113	4.5846	4.5373
N	39	39	39	39	39

Table IV. Volatility Measure Descriptive Statistics - Two-year Midcurve Options

This table presents the mean, standard deviation, skewness and kurtosis for the various measures of volatility. RV-IV and RV-HV are the differences between realized volatility and implied and historical volatility, respectively, in percent. * and ** represents significantly different from zero at the 5% and 1% level, respectively.

Panel A: Full Sample

	RV	IV	HV Ouch	IV - RV	HV - RV
μ	23.0000	24.9481	22.2831	1.9455 ***	-0.7169 ***
σ	11.5376	10.6368	10.3485	5.9752	7.3233
Skewness	1.1472	1.0048	1.1680	-0.1440	-0.7231
Kurtosis	0.72447	0.5737	2.0833	4.8895	2.0755
25th	14.0442	16.14253	14.0965	-0.4521	-3.3967
Median	19.5586	21.8850	19.9504	2.6446	0.6021
75th	30.2338	31.3854	28.4529	5.5341	4.1552
N	5960	5956	5960	5956	5960

Panel B: Non-overlapping One Month

	RV	IV	HV Ouch	IV - RV	HV - RV
μ	22.0256	23.2924	22.0675	1.2670	0.0421
σ	12.5576	11.2364	12.5185	5.0253	6.3352
Skewness	1.3598	1.3420	1.5934	-1.2181	-0.7144
Kurtosis	1.3543	1.6338	3.1229	3.3827	1.0263
25th	13.4148	14.9669	13.6858	-1.5793	-3.7065
Median	18.0911	19.5545	18.1044	2.4568	1.3030
75th	26.1471	28.7401	27.5507	4.0185	4.1836
N	40	40	40	40	40

Panel C: Non-overlapping Two Month

	RV	IV	HV Ouch	IV - RV	HV - RV
μ	22.2420	23.7149	21.7192	1.4729	-0.5229
σ	12.0261	10.1623	11.1804	5.5245	5.9863
Skewness	1.5717	0.9839	1.2203	-1.5782	-0.3304
Kurtosis	2.5839	-0.2376	0.7510	4.1253	1.1869
25th	12.8941	15.5734	13.5245	-0.6362	-3.4960
Median	18.5761	20.6636	18.5216	2.4177	-0.0988
75th	27.8786	41.7210	26.3800	5.1319	2.0250
N	40	40	40	40	40

Panel D: Non-overlapping Three Month

	RV	IV	HV Ouch	IV - RV	HV - RV
μ	21.7440	23.7867	21.8528	2.0426	0.1088
σ	11.6420	11.2167	11.0311	4.2487	6.6925
Skewness	1.5588	1.0727	1.1273	-0.8902	-0.6007
Kurtosis	2.4769	-0.1322	0.9892	1.8492	2.2819
25th	12.9821	14.6100	12.4558	0.3691	-1.7952
Median	17.9201	19.6572	18.3908	1.8465	0.1432
75th	25.2223	29.3064	30.2376	5.2555	3.0591
N	36	36	36	36	36

Table V. Unbiased Regression Test Results - Standard Options

This table presents the results of the regression $RV_t = \alpha + \beta IV_t + \gamma HVt + \varepsilon_t$ for standard options. RV_t is the realized annualized standard deviation of daily returns after date *t*. IV_t is the annualized implied volatility at date *t*. HV_t is the annualized historical volatility at date t. *, **, and *** represent significance at the 5%, 1%, and 0.1% level, respectively. The tests for the first two columns are the slope is unity. In the third column, the hypothesis is $\beta = 1$ and $\gamma = 0$. The last line presents the significance of the joint hypothesis over all parameters.

Panel A: Full Sample

	IV	HV OUCH	IV and HV
α	0.0093 ***	0.0640 ***	0.1160 ***
β	0.8812 ***		0.9740
γ		0.5939 ***	-0.0998 ***
Adj. R^2	0.6441	0.3833	0.6477
N	37732	37911	37732
Joint	***	***	***

Panel B: Non-overlapping One Month

	IV	HV OUCH	IV and HV
α	0.015304	0.0501 ***	0.016839
β	0.686113 ***		0.812352
γ		0.409198 ***	-0.13522
Adj. R^2	0.5113	0.2473	0.5161
N	85	85	85
Joint	***	***	***

Panel C: Non-overlapping Two Month

	IV	HV OUCH	IV and HV
α	0.0011	0.0408 ***	0.0021
β	0.8405 *		0.9160
γ		0.4705 ***	-0.0677
Adj. R^2	0.6827	0.4010	0.6818
N	84	84	84
Joint	***	***	***

Panel D: Non-overlapping Three Month

	IV	HV OUCH	IV and HV
α	0.0046	0.0442 ***	0.0053
β	0.7827 ***		1.0019
γ		0.4490 ***	-0.1842
Adj. R^2	0.6568	0.4092	0.6698
N	83	83	83
Joint	***	***	***

Table VI. Unbiased Regression Test Results - One-year Midcurve Options

This table presents the results of the regression $RV_t = \alpha + \beta IV_t + \gamma HVt + \varepsilon_t$ for one-year midcurve options. RV_t is the realized annualized standard deviation of daily returns after date *t*. IV_t is the annualized implied volatility at date *t*. HV_t is the annualized historical volatility at date t. *, **, and *** represent significance at the 5%, 1%, and 0.1% level, respectively. The tests for the first two columns are the slope is unity. In the third column, the hypothesis is $\beta = 1$ and $\gamma = 0$. The last line presents the significance of the joint hypothesis over all parameters.

Panel A: Full Sample

	IV	HV OUCH	IV and HV
α	0.0016	0.0447 **	0.0016
β	0.9892		0.8683 **
γ		0.9366 **	0.1359 **
Adj. R^2	0.7631	0.6647	0.7655
N	13526	13561	13526
Joint		***	***

Panel B: Non-overlapping One Month

	IV	HV OUCH	IV and HV
α	-0.02176 **	0.0115	-0.01774
β	1.0340		0.7816
γ		0.9613	0.2489
Adj. R^2	0.8505	0.8167	0.8509
N	40	40	40
Joint			

Panel C: Non-overlapping Two Month

	IV	HV OUCH	IV and HV
α	-0.0328	0.0193	-0.0261
β	1.0793		0.8830
γ		0.9778	0.1878
Adj. R^2	0.8495	0.8135	0.8475
N	40	40	40
Joint			

Panel D: Non-overlapping Three Month

	IV	HV OUCH	IV and HV
α	-0.0137	0.0353	-0.0169
β	1.0270		1.3701
γ		0.9454	-0.3645
Adj. R^2	0.8373	0.6941	0.8438
N	39	39	39
Joint			

Table VII. Unbiased Regression Test Results - Two-year Midcurve Options

This table presents the results of the regression $RV_t = \alpha + \beta IV_t + \gamma HVt + \varepsilon_t$ for two-year midcurve options. RV_t is the realized annualized standard deviation of daily returns after date *t* . IV_t is the annualized implied volatility at date *t* . HV_t is the annualized historical volatility at date t. *, **, and *** represent significance at the 5%, 1%, and 0.1% level, respectively. The tests for the first two columns are the slope is unity. In the third column, the hypothesis is $\beta = 1$ and $\gamma = 0$. The last line presents the significance of the joint hypothesis over all parameters.

Panel A: Full Sample

	IV	HV OUCH	IV and HV
α	-0.0022	0.0359 ***	-0.0028
β	0.9307 ***		0.8473 **
γ		0.8711 ***	0.0964
Adj. R^2	0.7359	0.6104	0.7374
N	5956	5960	5956
Joint	***	***	

Panel B: Non-overlapping One Month

	IV	HV OUCH	IV and HV
α	-0.0184	0.0271	-0.0168
β	1.0245		0.9559
γ		0.8751 *	0.0652
Adj. R^2	0.8361	0.7547	0.8322
N	40	40	40
Joint			

Panel C: Non-overlapping Two Month

	IV	HV OUCH	IV and HV
α	-0.0272	0.0193	-0.0188
β	1.0525		0.7629
γ		0.9352	0.2775
Adj. R^2	0.7854	0.7494	0.7857
N	40	40	40
Joint	*		

Panel D: Non-overlapping Three Month

	IV	HV OUCH	IV and HV
α	-0.0126	0.0267	-0.0118
β	0.9669		1.1426
γ		0.8729	-0.1945
Adj. R^2	0.8639	0.6748	0.8654
N	36	36	36
Joint	**		***

Table VIII. Profitability Test Results - Regular Options

This table shows the profitability of quarterly options of the unhedged and hedged portfolios for various initial maturities. The sell and hold portfolio sells the straddle and does not delta hedge. The rebalanced portfolio assumes futures are traded each day to make the portfolio delta neutral.*, **, and *** represent significance at the 5%, 1% , and 0.1% level, respectively.

Maturity Group		Number of Days	Average Investment	Average Delta	Sell and Hold Profit	Rebalanced Portfolio Profit
Days ≤ 63	μ	32.20	20.00	0.0277	-2.3129 **	-2.1938 **
N = 4676	σ	17.78	13.69	0.2643	20.7623	20.6803
	Min	2.00	0.25	-0.7554	-164.00	-169.9548
	Max	63.00	102.00	0.7744	86.00	88.5502
Days ≤ 42	μ	21.98	15.78	0.0252	-1.6812 **	-1.5864 **
N = 3129	σ	11.79	10.77	0.3034	15.6127	15.6596
	Min	2.00	0.25	-0.7554	-94.00	-110.5652
	Max	42.00	1.02	0.7744	86.00	88.5502
Days ≤ 21	μ	11.53	11.24	0.0244	-0.6314 *	-0.5399 *
N = 1526	σ	5.78	6.89	0.3614	10.6645	10.7303
	Min	2.00	0.25	-0.7554	-59.00	-69.2010
	Max	21.00	42.00	0.7744	32.00	30.1954

Figure 1: The Term Structure of Implied Volatility

This figure displays the term structure of volatility for regular and midcurve options on Eurodollar futures. The maturity groups are 1.5 months or less (1), 1.5 to 2.5 months (2), 2.5 to 4.5 months (3), 4.5 to 7.5 months (6), 7.5 to 10.5 months (9), 10.5 to 13.5 months (12), 13.5 to 16.5 months (15), 16.5 to 19.5 months (18), 19.5 to 22.5 months (21), and over 22.5 months (24). The mean, median, 25th percentile and 75th percent are displayed.