Pricing Currency Options with Intra-Daily Implied Volatility

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Abstract

In this paper we introduce a new volatility measure for pricing foreign exchange (FX) currency options based on implied volatility estimated on equally spaced intra-daily intervals. We also investigate whether this intra-daily implied volatility (IDIV) measure is pricing currency options more accurately than standard estimates of volatility. The implied volatility (IV) and realized volatility (RV) are widely accepted as good estimates of daily and intra-daily price volatility, respectively. Therefore, using the options pricing framework, we assess the capability of IDIV against IV and RV in pricing foreign currency options. The comparison of out-of-sample forecasts under both the F-test and Diebold-Mariano test reveals that the IDIV outperforms both the IV and the RV for estimating one-day-ahead option prices. In other words, the IDIV estimation framework provides a more accurate/efficient volatility estimate for pricing FX currency options.

1.0. Introduction

To properly price currency options, an accurate prediction of foreign exchange (FX) volatility is crucial. The implied volatility (IV) is widely used as a good estimate of FX volatility for pricing options. However we believe that the daily level IV weakens the ability to capture the complete intraday information, which is essential for accurately forecasting FX movement for pricing options. This study therefore introduce intra-daily implied volatility (IDIV) to obtain whole trading day market aggregate information for pricing currency options with higher accuracy.

In the early research, using data from currency options, Scott and Tucker (1989) find that IV derived from currency options captures nearly 50 percent of the actual currency volatility. When historical volatility is included in the investor's information set, the authors find no evidence of improved predictive accuracy. Jorion (1995) examines the predictive power of IV for the German mark, the Japanese yen and the Swiss franc against the U.S. dollar, traded in the Chicago Mercantile Exchange. Jorion's results suggest that IV outperforms statistical time-series models in terms of information content and predictive power, but it appears to be upwardly biased estimator of future volatility. Xu and Taylor (1995) examine the informational efficiency of the currency options market in the Philadelphia Stock Exchange. They studied four currencies (the British pound, the German mark, the Japanese yen and the Swiss franc against the U.S. dollar) over the period ranging from January 1985 to January 1991. They find that option prices contain incremental information about future volatilities. Christoffersen and Mazzotta (2005) use over-the-counter (OTC) currency options prices and find that the IV provides largely unbiased and fairly accurate forecasts of one-month-ahead and three-month-ahead actual volatility. Chang and Tabak (2007) present evidence that the IV in option prices contains information that is not present in past returns for the Brazilian exchange rate against the U.S. dollar.

The above-mentioned studies involving IV often find that all the relevant information for FX volatility prediction can be found in the options price. However, we argue that IV holds the discrete information of the FX movement for the specific time of the trading day and is therefore insufficient for estimating accurate options price. For example, the IV based on the closing options price information of trading day *t* might not be an appropriate performance measurement to forecast the opening or midday options price of trading day *t+1*. Therefore, we developed the IDIV model to capture the intra-daily level aggregate information related to FX behavior, which changes every five minutes, to correctly estimate the one-day-ahead currency options price.

This study provides two major contributions to the literature. First, while IV is widely used for predicting FX volatility, to the best of our knowledge, IDIV has not yet been explored to forecast FX volatility for pricing options. Second, Pong et al. (2004) show that a forecast based on RV provides superior accuracy relative to a forecast based on IV. Martin and Zein (2004) present similar results for equity and commodities in addition to currency. It is inappropriate to compare, however, the forecasting capability of RV and IV since both of these are constructed with different levels of data. This study evaluates the performance differences between RV and IDIV, based on the same level of intra-daily FX return.

We find that IDIV outperforms IV for pricing options. Further the outstanding performance of IDIV against RV substantiates its ability for pricing option. This also indicates that the RV contains intra-daily historical information that is not as appropriate for accurately forecasting price options as the information obtained from the IDIV. The paper is organised as follows: Section 2 presents the research methodology, Section 3 describes the data used in this study, Section 4 provides the empirical analysis and Section 5 concludes the paper.

2.0. Methodology

This study's methodology is divided into two stages: (i) estimate the IDIV, IV and RV; (ii) forecast options price using volatilities in stage (i) as input for the pricing model and measure forecast pricing error.

2.1. Estimate Volatilities

The following sub-sections discuss the IDIV, IV and RV estimation methods used in this study.

Intra-daily implied volatility

To calculate IDIV, first we obtain implied volatility at intra-daily level using equations (A5) and (A6) from appendix for call (C) and put (P) option, respectively. The annualized IDIV is computed as in equation (1):

$$\sigma_t^{IDIV} = \sum_{i=1}^{n} w_{C,i}\, \sigma_{C,i} + w_{P,i}\sigma_{P,i}, \qquad (1)$$

where n is the total number of intervals between 9:30 AM to 4:00 PM of trading day t. In equation (1), $w_{C,i}$ and $w_{P,i}$ denote the call and put intra-daily level implied volatility weight, respectively, for the 5-min interval. For each interval, $w_{C,i}$ is calculated as the total number of call transactions divided by the sum of the total number of call and put transactions (i.e. the total number of call ÷ (total number of call + total number of put)). Similarly, for each interval $w_{P,i}$ is calculated as the total number of put transactions divided by the sum of the total number of call and put transactions (i.e. total number of put ÷(total number of call + total number of put)). The sum of $w_{C,i}$ and $w_{P,i}$ is equal to 1.

Implied volatility

Gospodinov et al. (2006) suggest that an unbiased IV can be extracted from near-the-money options. DATASTREAM provides the call implied daily volatility $\sigma_{C,t}$ and put implied volatility $\sigma_{P,t}$, which are interpolated using the nearest at-the-money (ATM) two options series, one above and one below the underlying FX in the financial system software developed by MB Risk Management (MBRM). MBRM developed the world-famous UNIVERSAL Add-ins® . With 30,000+ users worldwide, UNIVERSAL Add-ins is the most widely-used derivative software for the pricing, risk management, trading, arbitrage, fund management and auditing of securities, options, futures and swaps in the convertible, fixed income, commodities, energy, equities, foreign exchange and money markets (see more at website http://www.mbrm.com). Jorion (1995) computes IV as the arithmetic average that is obtained from the two closest ATM call and put options. Thus, this study estimates the annualized IV on any given day *t* as the arithmetic average of $\sigma_{C,t}$ and $\sigma_{P,t}$,

$$\sigma_t^{IV} = \frac{\sigma_{C,t}+\sigma_{P,t}}{2}. \qquad (2)$$

Realized volatility

The RV is constructed by summing the squared intra-day returns sampled at a particular frequency. The optimal frequency for constructing RV is unknown. Following the standard practice, the RV series is constructed using a 5-min sampling frequency. If S_i is the exchange rate for the 5-min sampling frequency, the underlying exchange rate return in the 5-min interval is estimated as:

$$r_i = ln\left(\frac{S_i}{S_{i-1}}\right) .$$

The realized variance of day t is computed as:

$$v_t = \sum_{i=1}^{n} r_i^2,$$

Where *n* is the total number of intervals from 9:30 AM to 4:00 PM for the trading day. Since RV is the standard deviation of the realized variance, the annualized RV for the trading day t is:

$$\sigma_t^{RV} = \sqrt{Dv_t}, \quad (3)$$

where D is 252 trading days per year consistent with the normal assumption of the options market.

2.2. Measure Forecast Pricing Error

To forecast one-day-ahead opening, midday and closing C and P option price, equation (4) is developed using the MATLAB built-in function "blsprice" which embeds equations (A1) and (A2) from appendix,

$$|C,P|_t^m = blsprice\left(S_t,\ X_t, R_t^d, T,\ \sigma_{t-1}^m, R_t^f\right), \quad (4)$$

where, $\forall_m = IDIV, IV, RV$.

Further, if π_t denotes the difference between the forecasted options price and market options price, the mean square pricing error for *n* number of observations is

$$MSPE_j = \frac{1}{n}\sum_{t=1}^{n} \pi_{t,j}^2 \ ,$$

where $\forall_j = C, P$.

Next, the F-test is modeled as:

$$F_j^{l,IDIV} = \frac{MSPE_j^l}{MSPE_j^{IDIV}}, \quad (5)$$

where, $\forall_l = IV, RV$. The null hypothesis $H_0: MSPE_j^l = MSPE_j^{IDIV}$ is tested against the alternative hypothesis $H_A: MSPE_j^l > MSPE_j^{IDIV}$.

The MSPE criterion under F-test compares options price forecasting performance of IDIV against IV and RV. Therefore, it is important to test whether the pricing errors of IDIV is statistically different from that of IV and RV. Diebold and Mariano (1995) proposed a test statistic that there is no difference in the accuracy of two competing forecasts. In the Diebold and Mariano (DM) test, the mean differential loss from $\left(\pi_{t,j}^{l}\right)^2$ and $\left(\pi_{t,j}^{IDIV}\right)^2$ is estimated as:

$$\overline{d} = \frac{1}{n}\sum_{t=1}^{n}\left|\left(\pi_{t,j}^{l}\right)^2 - \left(\pi_{t,j}^{IDIV}\right)^2\right|.$$

Under the null hypothesis of the accuracy of the equal one-day-ahead pricing error, the value of $\bar{\mathrm{d}}$ is zero. The DM statistic is given by:

$$DM_j^{l,IDIV} = \frac{\overline{d}}{\sqrt{var(\overline{d})}}, \qquad (6)$$

where, $var(\overline{d}) = \frac{1}{n-1}var(d_t)$. Equation (6) follows a t-distribution with $(\mathrm{n}-1)$ degrees of freedom.

3.0. Data Descriptions

This study includes the six major currency options for the Australian dollar (AUD), the Canadian dollar (CAD), the Swiss franc (CHF), the Euro (EUR), the British pound (GBP) and the Japanese yen (JPY) are obtained from options price reporting authority (OPRA). The sample period starts from 21/12/2009 for all currency except AUD, which is started from 21/06/2010. The difference in start dates is due to the unavailable of the AUD put-call pair from 21/12/2009 (Monday) to 18/06/2010 (Friday). However, the sample periods for all the currency in this study end on 27/05/2011. Consequently, the AUD sample period includes 238 trading days, whereas the remaining currency options are sampled for 362 trading days.

In this study, the intra-daily and daily data are obtained from SIRCA and DATASTREAM, respectively.

The intra-daily data from the SIRCA database consists of call, put, strike and spot price transactions at 5-min intervals from 9:30 AM to 4:00 PM of the trading day. The high frequency intra-daily level data analysis is given in Table 1. The sample currency names are given in the first column and rest of the Table is divided into Panel A and Panel B. The information in Panel A describes the construction of a put-call pair for IDIV. Column 3 and Column 4 of Panel A present the 5-min interval for 'total transaction' and 'sample transaction', respectively. For the 'total transaction', the 5-min interval put-call pair holds one or more transactions. Therefore, the 'sample transaction' is constructed by filtering the 'total transaction' that has only one put-call pair in the 5-min interval. In last column, the 'average daily transaction' is computed as the 'sample transaction' divided by the 'trading days' from Column 2. The average daily transaction should be 79 for the 9:30 AM to 4:00 PM trading hours. For all the currency, an 'average daily transaction' of less than 79 indicates that some of the 5-min intervals do not have a put-call pair transaction.

The information in Panel B defines two different spot price data sets for RV: (i) the FX return for a transaction at the 5-min interval and (ii) the FX return for a transaction at the 5-min interval that matches the put-call pair transaction. For data set (i), the 'average daily FX return' is calculated as the 'total FX return' in Column (2) divided by the 'trading days' from Column 2 of Panel A. Similarly, the 'average daily FX return' of data set (ii) is computed using the 'total FX return' in Column (4) and the 'trading days' from Column 2 of Panel A. For all currency, the data set (i) provides and 'average daily FX return' of 71 (5 from 9:30 am to 10:00 am and 11 for each from 10:00 am to 4:00 pm), which is expected for the 9:30 AM to 4:00 PM trading hours (i.e. 5 from 9:30 am to 10:00 am and 11 for each from 10:00 am to

4:00 pm). Since the data set (ii) is constructed with matching put-call pair transactions and some of the 5-min intervals do not have a put-call pair transaction (as reported in Panel A), the 'average daily FX return' of data set (ii) is less than that of data set (i), for all the sample currency. The data set (ii) will be used to conduct a robustness test for IDIV and RV pricing options.

< Insert Table 1 here>

Intra-daily data obtained from SIRCA are also used to determine the opening, midday and closing options market prices. The first available 5-min interval price between 9:30 AM and 10:00 AM is considered to be the 'opening price'. Similarly, the period from 12:30 PM to 1:00 PM is used to pick up the first available 5-min interval price and is considered to be the 'midday price'. The 'closing price' includes the first 5-min interval price between 3:30 PM and 4:00 PM.

The daily data obtained from DATASTREAM consist of the daily nearest ATM call and put implied volatility and the risk-free closing domestic and foreign interest rates. The daily nearest ATM strike and spot price is also obtained in order to assess the quality of the daily DATASTREAM interpolated implied volatility for call (call-IV) and implied volatility for put (put-IV). The descriptive statistics of strike price, spot price, call-IV and put-IV are given in Table 2. The mean values of the strike price and the spot price are the same for all the currency. Furthermore, the median values for the strike price and the spot price are very close. Therefore, we conclude that the DATASTREAM interpolated call IV and put IV using currency options are traded at the nearest ATM. The information in Column 5 and Column 6 provides the mean and median of the call-IV and put-IV, respectively. Whaley (1986) shows that call-IV is on average lower than put-IV. We find similar results for the AUD, BP and

CAD options (for example, for AUD the mean of the call IV and the put IV is 12.92% and 12.98%, respectively).

< Insert Table 2 here>

4.0. Empirical Analysis

Empirical analysis is carried out into three steps: (i) forecast one-day-ahead opening, midday and closing options price as in equation (4); (ii) conduct an F-test by equation (5) to examine the MSPE equality for IDIV against IV and RV; (iii) DM-test is performed using equation (6) to determine whether MSPE for IDIV is statistically different from that of IV and RV.

Table 3 provides an analysis of the IV and IDIV opening, midday and closing options price forecasting errors as noted in Panels A, B and C, respectively. The results are presented as the 'call MSPE equality test' (Columns 2 to 4), the 'put MSPE equality test' (Columns 5 to 7) and the DM-test (Columns 8 and 9). For all the currency listed in Panel A, the F-values in Columns 4 and 7 indicate that $\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{IV}}$ (Column 2) and $\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{IV}}$ (Column 5) are larger than $\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{IDIV}}$ (Column 3) and $\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{IDIV}}$ (Column 6), respectively. Under the DM-test, the T-stat values (i.e. T-statistic) for the call and the put in Columns 8 and 9 reveal that $\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{IV}}$ and $\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{IV}}$ are statistically different from $\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{IDIV}}$ and $\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{IDIV}}$, respectively. Furthermore, the positive T-stat values suggest that $\mathrm{MSPE}_{\mathrm{c}}^{\mathrm{IV}}$ and $\mathrm{MSPE}_{\mathrm{p}}^{\mathrm{IV}}$ have a greater value than $\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{IDIV}}$ and $\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{IDIV}}$, respectively. Panel B and Panel C provide similar results for all the sample currency. The consistent findings in the series of F-tests and DM-tests for the opening, midday and closing prices across the six major currency options confirm that the FX forecasting capability of IDIV is better than the FX forecasting capability of IV for pricing one-day-ahead options.

< Insert Table 3 here>

Next, the RV and IDIV opening, midday and closing options price forecasting error analysis results are given in Panels A, B and C, respectively (Table 4). Note that the RV is estimated using the intra-daily level data set (i) in Panel B (Table 1). The data population structure of Table 4 is the same as Table 3. For all the currency in Panels A, B and C, the F-test results show that $\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{RV}}$ and $\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{RV}}$ have a larger value than $\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{IDIV}}$ and $\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{IDIV}}$, respectively. We found similar results using the DM-test. The F-test and DM-test results are consistent across the six major currency options, which implies that IDIV outperforms RV for forecasting FX volatility for the next-day options price.

< Insert Table 4 here>

Finally, RV is estimated using intra-daily data set (ii) in Panel B (Table 1) to conduct the RV and IDIV price forecasting error robustness test. The test results are presented in Table 5. The construction and results interpretation of Table 5 are similar to Table 4. The overall F-test and DM-test results are consistent with the results reported in Table 4. This means that the robustness test results substantiate the statement that IDIV is superior to RV for forecasting FX movement for the one-day-ahead options price.

< Insert Table 5 here>

5.0. Conclusion

Predicting FX volatility for pricing options is critical. In the literature, the IV is considered to be a good estimator of exchange rate volatility. Since the IV contains information for the specific time of the trading day, the IDIV is modeled to accurately capture intra-daily trading day information for pricing options. The IDIV and IV are used as inputs for the Merton version of the Black-Scholes model, which is used to estimate the one-day-ahead options price. The MSPE for IDIV and IV is calculated as the difference between the options market price and the options forecasted price using IDIV and IV, respectively. Under the F-test and the DM-test, the smaller MSPE for IDIV indicates that IDIV outperforms IV for pricing options.

The forecasting performance differences between IDIV and IV might be arguable since the IDIV and the IV contain different levels of market information, that is, intra-daily and daily level information, respectively. To address this argument, the RV is used as benchmark to compare the forecasting power of IDIV for pricing options. The RV is constructed based on two different sets of intra-daily level data: (i) FX returns for 5-min intervals and (ii) FX returns for 5-min intervals that are matched with the put-call pair frequency. For both data sets, the F-test and the DM-test confirm that IDIV is also superior to RV for pricing options since the MSPE for RV has a larger value relative to the value of the MSPE for IDIV.

We believe that the IDIV is a unique approach that adds a new dimension for options market volatility to the literature. Traders can take advantage of this by using IDIV to accurately forecast pricing options. Researchers can use these IDIV insights to further study options market volatility. Since currency options mature on the third Friday of each month, IDIV options pricing performance needs to be examined for a one-month horizon in order to support its uniqueness. We have left that analysis for future research.

Appendix

The intra-daily level implied volatility (IDIV) is the volatility that is implied by the intra-daily options market price using the options pricing model. Black and Scholes (1973, BS) first derived a closed form solution for pricing European options. The BS model assumes that no dividends are paid on the stock during the life of the option. Merton (1973) extended this model to cover continuous dividends. Since the interest gained on holding a foreign security is equivalent to a continuously paid dividend on a stock, the Merton version of the BS model can be applied to foreign security. To value the currency option, stock prices are substituted for exchange rates. Following Biger and Hull (1983), the price of a European type call and put option on currency is given in equation (A1) and (A2), respectively,

$$C_i = S_i e^{-R_t^f T} N(d_{1,i}) - X_i e^{-R_t^d T} N(d_{2,i}), \qquad \text{(A1)}$$

$$P_i = X_i e^{-R_t^d T} N(-d_{2,i}) - S_i e^{-R_t^f T} N(-d_{1,i}), \qquad \text{(A2)}$$

where,

$$d_{1,i} = \frac{ln(S_i/X_i) + \left(R_t^d - R_t^f + \sigma_i^2/2\right)T}{\sigma_i\sqrt{T}} \text{ and}$$

$$d_{2,i} = \frac{ln(S_i/X_i) + \left(R_t^d - R_t^f - \sigma_i^2/2\right)T}{\sigma_i\sqrt{T}} = d_{1,i} - \sigma_i\sqrt{T}\ .$$

The notations of equation (A1) and (A2) and their descriptions are as follows:

C	call option price in domestic currency
P	put option price in domestic currency
S	spot price in terms of domestic currency
X	option exercise price in domestic currency
R^d	domestic currency interest rate
R^f	foreign currency interest rate
T	option maturity period
σ	volatility of underlying currency
N(·)	cumulative normal distribution function

For notation convenience, let $\xi_t = e^{-R_t^f T}$ and $\eta_t = e^{-R_t^d T}$, so that equations (A1) and (A2) can be written as follows:

$$C_i = S_i \xi_t N\left[d_{1,i}(\sigma_i)\right] - X_i \eta_t N\left[d_{2,i}(\sigma_i)\right], \qquad \text{(A3)}$$

$$P_i = X_i \eta_t N\left[-d_{2,i}(\sigma_i)\right] - S_i \xi_t N\left[-d_{1,i}(\sigma_i)\right] \qquad \text{(A4)}$$

The intra-daily level implied volatility is σ_i, and when substituted into equations (A3) and (A4) it gives the market call and put price, respectively. It is not possible to invert equations (A3) and (A4) with respect to σ_i. Alternatively, an iterative search procedure can be used to find the implied volatility for given options market prices. The Newton-Raphson and Dekker-Brent methods (see Press et al. 1992), the two most popular iterative solver methods, are used frequently. The Newton-Raphson method uses derivative information and has quadratic convergence speed. The Dekker-Brent method uses a combination of the bisection, scant and inverse quadratic interpolation methods and is guaranteed to converge. The Newton-Raphson method is faster in processing but less robust than the Dekker-Brent method. In practice, due to its robustness, the Dekker-Brent method is often chosen over the Newton-Raphson method.

The Dekker-Brent method is used as an iterative solver for the MATLAB built-in function "blsimpv", which embeds equations (A3) and (A4), as shown in equations (A5) and (A6), respectively, with a default volatility upper bound limit 1000% per annum and a termination tolerance 0.0001. For every 5 minute (5-min) interval, equations (A5) and (A6) calculate the intra-daily level implied volatility for the call and put price, respectively, as follows:

$$\sigma_{C,i} = blsimpv\left(S_i,\ X_i, R_t^d, T, C_i, Limit, R_t^f, Tolerance, \{'call'\}\right), \qquad \text{(A5)}$$

$$\sigma_{P,i} = blsimpv\left(S_i,\ X_i, R_t^d, T, P_i, Limit, R_t^f, Tolerance, \{'put'\}\right). \qquad \text{(A6)}$$

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Table 1: SIRCA intra-daily data analysis

Currency	Panel A: put-call pair data set for IDIV			
	trading days	total transaction	sample transaction	average daily transaction
AUD	238	1,092,604	18,078	76
CAD	362	1,483,583	25,967	72
CHF	362	1,079,024	24,456	68
EUR	362	2,769,536	26,129	72
GBP	362	1,571,583	25,050	69
JPY	362	1,332,328	24,394	67

Currency	Panel B: spot price data set for RV			
	data set (i) FX return for 5-min interval		data set (ii) FX return for 5-min interval that matches the put-call pair transaction	
	total FX return	average daily FX return	total FX return	average daily FX return
AUD	16,898	71	16,234	68
CAD	25,670	71	22,773	63
CHF	25,695	71	21,294	59
EUR	25,695	71	23,233	64
GBP	25,695	71	21,758	60
JPY	25,695	71	21,478	59

Table 2: DATASTREAM daily data descriptive analysis

currency	statistical measures	variables			
		strike price	spot price	call IV	put IV
AUD	Mean	97.9225	97.9182	0.1292	0.1298
	Median	99.0000	98.9900	0.1263	0.1267
BP	Mean	156.6445	156.6639	0.1083	0.1085
	Median	157.5000	157.3400	0.1056	0.1061
CAD	Mean	98.5360	98.5386	0.1065	0.1068
	Median	98.0000	98.1100	0.1053	0.1056
EUR	Mean	134.8960	134.8849	0.1211	0.1204
	Median	136.0000	135.8200	0.1181	0.1166
JPY	Mean	116.1791	116.1800	0.1149	0.1131
	Median	118.1800	118.0000	0.1131	0.1107
SF	Mean	99.76667	99.7551	0.1130	0.1118
	Median	98.5000	98.5500	0.1115	0.1104

Notes: Each currency sample size is 362 except AUD which is 238.

Table 3: IV and IDIV price forecasting error analysis								
Currency	call MSPE equality test			put MSPE equality test			DM-test	
	$MSPE_C^{IV}$	$MSPE_C^{IDIV}$	F-value	$MSPE_P^{IV}$	$MSPE_P^{IDIV}$	F-value	call T-stat	put T-stat
Panel A: opening price								
AUD	5.2743	5.2313	1.0082	25.9839	25.8966	1.0034	9.5399	9.3878
CAD	7.3257	7.2887	1.0051	9.4870	9.4445	1.0045	7.8145	8.2976
CHF	7.6913	7.6468	1.0058	7.0686	7.0600	1.0012	11.9152	11.9864
EUR	14.8366	14.7573	1.0054	17.0006	16.9149	1.0051	8.0578	8.1490
GBP	18.7107	18.5527	1.0085	22.0190	21.8448	1.0079	9.4046	9.5882
JPY	13.8257	13.7447	1.0059	12.7390	12.6592	1.0063	9.1232	9.7135
Panel B: midday price								
AUD	7.1359	7.0492	1.0122	34.1578	33.9698	1.0055	17.4849	16.9195
CAD	6.8944	6.8466	1.0070	8.9431	8.8883	1.0062	10.3940	10.8576
CHF	8.0847	8.0429	1.0052	7.3411	7.3017	1.0054	11.7083	11.6739
EUR	17.8007	17.7213	1.0045	20.4471	20.3622	1.0042	7.6674	7.6753
GBP	21.4880	21.2938	1.0091	25.8580	25.6420	1.0084	9.9064	10.6304
JPY	12.9831	12.8991	1.0065	11.5282	11.4474	1.0071	11.2861	12.0425
Panel C: closing price								
AUD	6.2164	6.1527	1.0103	29.3182	29.1833	1.0046	13.4448	12.7952
CAD	5.6911	5.6625	1.0051	7.4113	7.3784	1.0045	7.0728	7.4112
CHF	6.6487	6.6249	1.0036	5.9851	5.9624	1.0038	8.6526	8.7788
EUR	14.7981	14.7461	1.0035	16.7089	16.6544	1.0033	6.1969	6.1210
GBP	18.3212	18.1856	1.0075	22.4589	22.3115	1.0066	8.5613	8.5507
JPY	11.1949	11.1480	1.0042	10.0344	9.9894	1.0045	5.5880	5.7238

Notes: MSPE denotes the mean square pricing error. T-stat representing the T-statistic of DM-test. F-test critical value is 1 for the F-distribution with more than 120 degrees of freedom for both numerator and denominator.

Table 4: RV and IDIV price forecasting error analysis

Currency	call MSPE equality test			put MSPE equality test			DM-test	
	$MSPE_C^{RV}$	$MSPE_C^{IDIV}$	F-value	$MSPE_P^{RV}$	$MSPE_P^{IDIV}$	F-value	call T-stat	put T-stat
Panel A: opening price								
AUD	5.5285	5.2313	1.0568	26.4930	25.8966	1.0230	19.4517	18.6189
CAD	7.5286	7.2887	1.0329	9.7186	9.4445	1.0290	16.8712	16.9788
CHF	7.9335	7.6468	1.0375	7.2921	7.0160	1.0394	21.3842	21.6257
EUR	15.5463	14.7573	1.0535	17.7527	16.9149	1.0495	23.0678	23.0176
GBP	19.2377	18.5527	1.0369	22.5852	21.8448	1.0339	14.9149	14.9991
JPY	14.3154	13.7447	1.0415	13.2094	12.6592	1.0435	19.8493	19.7390
Panel B: midday price								
AUD	7.5904	7.0492	1.0768	35.1089	33.9698	1.0335	33.2099	30.9616
CAD	7.1135	6.8466	1.0389	9.1914	8.8883	1.0341	18.4539	18.8550
CHF	8.3639	8.0429	1.0399	7.6087	7.3017	1.0420	23.0535	22.9202
EUR	17.7213	16.6586	1.0637	21.3572	20.3622	1.0489	26.6625	26.3024
GBP	22.2465	21.2938	1.0447	26.6756	25.6420	1.0403	21.3498	21.3317
JPY	13.5390	12.8991	1.0496	12.0570	11.4474	1.0533	21.7424	21.8637
Panel C: closing price								
AUD	6.5454	6.1527	1.0638	29.9799	29.1833	1.0272	22.9721	21.7419
CAD	5.8566	5.6625	1.0342	7.5976	7.3784	1.0297	14.9683	15.2571
CHF	6.8360	6.6249	1.0319	6.1652	5.9624	1.0340	16.5124	16.5825
EUR	15.4083	14.7461	1.0449	17.3507	16.6544	1.0418	19.5402	19.1298
GBP	18.8586	18.1856	1.0370	23.0416	22.3115	1.0327	15.3695	15.5173
JPY	11.5676	11.1480	1.0376	10.3940	9.9894	1.0405	15.2149	15.2832

Notes: See the notes of Table 3.

Table 5: The RV and IDIV price forecasting error robustness test

Currency	call MSPE equality test			put MSPE equality test			DM-test	
	$\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{RV}}$	$\mathrm{MSPE}_{\mathrm{C}}^{\mathrm{IDIV}}$	F-value	$\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{RV}}$	$\mathrm{MSPE}_{\mathrm{P}}^{\mathrm{IDIV}}$	F-value	Call T-stat	Put T-stat
panel A: opening price								
AUD	5.5357	5.2313	1.0582	26.5080	25.8966	1.0236	19.2329	18.3708
CAD	7.5519	7.2887	1.0361	9.7446	9.4445	1.0318	16.5232	16.7603
CHF	7.9802	7.6468	1.0435	7.3372	7.0160	1.0458	21.2098	21.3645
EUR	15.5962	14.7573	1.0568	17.8077	16.9149	1.0528	22.6940	22.6634
GBP	19.3464	18.5527	1.0428	22.7035	21.8448	1.0393	14.6664	14.7602
JPY	14.3658	13.7447	1.0452	13.2579	12.6592	1.0473	19.6787	19.5545
panel B: midday price								
AUD	7.5948	7.0492	1.0123	35.1182	33.9698	1.0338	32.9025	30.7635
CAD	7.1394	6.8466	1.0428	9.2213	8.8883	1.0375	17.9187	18.3094
CHF	8.4037	8.0429	1.0449	7.6465	7.3017	1.0472	23.9086	23.6150
EUR	18.7023	17.7213	1.0554	21.4028	20.3622	1.0511	26.5877	26.2819
GBP	22.3774	21.2938	1.0509	26.8193	25.6420	1.0459	20.9945	20.9755
JPY	13.5767	12.8991	1.0525	12.0918	11.4474	1.0563	21.4573	21.6658
panel C: closing price								
AUD	6.5528	6.1527	1.0650	29.9951	29.1833	1.0278	22.5900	21.4032
CAD	5.8846	5.6625	1.0392	7.6292	7.3784	1.0339	14.2715	14.5969
CHF	6.8589	6.6249	1.0353	6.1871	5.9624	1.0377	16.5279	16.5772
EUR	15.4360	14.7461	1.0468	17.3802	16.6544	1.0436	19.4010	19.0036
GBP	18.9370	18.1856	1.0413	23.1273	22.3115	1.0366	15.3159	15.4493
JPY	11.5964	11.1480	1.0402	10.4203	9.9894	1.0431	15.0294	15.1756

Notes: See the notes of Table 3.