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Pricing European Currency Options with High-Frequency Data

Thi Le [1,2,*] and Ariful Hoque [2]

[1] CRTRAD, Thuongmai University, Hanoi 10000, Vietnam
[2] Murdoch Business School, Murdoch University, Perth 6150, Australia
* Correspondence: quynh.ltn@tmu.edu.vn; Tel.: +618-9360-6028

Abstract: Technological innovation has changed the financial market significantly with the increasing application of high-frequency data in research and practice. This study examines the performance of intraday implied volatility (IV) in estimating currency options prices. Options quotations at a different trading time, such as the opening period, midday period and closing period of a trading day with one-month, two months' and three months' maturity, are employed to compute intraday IV for pricing currency options. We use the Mincer–Zarnowitz regression test to analyse the volatility forecast power of IV for three different forecast horizons (within a week, one week and one month). Intraday IV's capability in estimating currency options price is measured by the mean squared error, mean absolute error and mean absolute percentage error measure. The empirical findings show that intraday IV is the key to accurately forecasting volatility and estimating currency options prices precisely. Moreover, IV at the closing period of the beginning of the week contains crucial information for options price estimation. Furthermore, the shorter maturity intraday IV is suitable for pricing options for a shorter horizon. In comparison, the intraday IV based on the longer maturity options subsumes appropriate information to price options with higher accuracy for the longer horizon. Our paper proposes a new approach to accurately pricing currency options using high-frequency data.

Keywords: high-frequency data; intraday IV; European currency options pricing; realised volatility

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1. Introduction

Financial markets have overseen several significant changes in recent years due to technological innovation, policy reforms, and increased competition. These changes involve the growth of a modern type of high-frequency trading (HFT), which has become a prevalent feature of today's markets (Linton and Mahmoodzadeh 2018). HFT refers to a trading method where security positions are switched over rapidly using advanced technology and innovative trading infrastructures (Agarwal 2012). In a comparatively short time, HFT has obtained a substantial share of the total US and European stock trading volume and quickly gained traction in other regions such as Asia-Pacific. The massive increase in HFT trade volumes and trade value are estimated to be continued by better access to the new technologies that enable it. The market size of HFT in the US is anticipated to be $6.1 billion, with an annual market size growth rate of 1.5% for the period between 2016 and 2021 (IBISWorld 2020). The emergence of HFT results in the vast information available for market participants to explore financial market phenomena. It is a reliable source of intraday information to guide investment decisions that cover a diverse range of assets and instruments such as commodities, derivatives, equities, fixed income and foreign exchange (FX) (Le et al. 2021).

Foreign currency options are the key innovation that contributes significantly to the sustainable development of the financial market. Its trading volume experienced significant growth during the last three decades. The BIS (2019) survey report shows that in 24 years since 1995, the over-the-counter (OTC) daily turnover in currency options increased from 41 billion US dollars to 294 billion US dollars, corresponding to more than 617%. Both academics and market practitioners primarily employ the Black and Scholes (1973) (BS) model to calculate European options prices (Yang and Lee 2011). For the Merton (1973) version of the Black and Scholes (1973) (BSM) model, all input elements to calculate prices for European currency options are obtainable from the financial market, except the volatility of the underlying currency. The volatility estimated error leads to options mispricing (Tu et al. 2016; Cruz 2008; Singh and Vipul 2015). Mispricing affects the choice of hedge ratios, hedge efficiencies, expected hedging costs (Lai et al. 2017) and market efficiency. The use of volatility that is not equivalent to the actual volatility over the lifespan of options will significantly impact the expected return and trader's portfolio risk (Figlewski 1989). Volatility measurement accuracy is, therefore, necessary to accurately estimate and predict currency options prices.

The availability of high-frequency data has motivated a pricing model that considers intraday data to estimate and forecast daily volatility. A tremendous amount of information can be found in five minutes of foreign exchange returns when measuring hourly variances (Taylor and Xu 1997; Barndorff-Nielsen and Shephard 2002). In addition, Wang and Wang (2016) reported the value of IV information at different trading times during a trading day to forecast the realized volatility of the S&P 500. However, research on forecasting FX volatility and currency options prices using high-frequency data is still limited. This study examines the intraday IV capability to forecast currency options price by (i) evaluating the intraday IV ability to forecast the underlying FX volatility and (ii) assessing the IV's performance in pricing currency options. We employ the high-frequency dataset of three major European currency options, including CHF, EUR, and GBP, from 2010 to 2020.

This study has four significant contributions. Firstly, it proposes an intraday IV approach to estimate the currency options price based on high-frequency data extracted from a trading day's different trading times. This method conquers the most critical FX information in pricing currency options. Most previous research used high-frequency data of stock markets (Wang and Wang 2016) or one particular currency such as AUD (Le et al. 2021), or EUR (Plíhal and Lyócsa 2021) to forecast realized volatility. This research focuses on the foreign exchange market using three major European currency options. Secondly, outcomes of the research reveal that the intraday IV based on one and two months of maturity options subsumes the required information to forecast the underlying FX volatility for the forecast horizon of one week and one month, respectively. However, the three-month maturity IV was found to contain no required information to price options accurately. Thirdly, the intraday IV based on the shorter maturity options is suitable for pricing options for a shorter horizon. In comparison, the intraday IV based on the longer maturity options subsumes the required information for the longer horizon options price. Fourthly, the IV's information is irrelevant for the price of less than a week horizon options.

The remaining paper is organised as follows. The next section begins with a review of IV literature, followed by methodology and data description. Section 4 conducts the empirical analysis and discusses the findings. Finally, Section 5 provides the research conclusion, limitations, and future directions.

2. Literature Review

The volatility of the underlying assets obtained in the BS option pricing models (Raquel and Eliseo 2012) is called Implied volatility (IV). It is calculated based on the option price observed in the market and is accepted as a fair measure of the underlying asset's volatility by the perception of market participants. The IV is, therefore, regarded as forward-looking. Research on the predictability of IV is ambiguous, with various inconsistencies. However, it appears that IV contains essential information about forecasted volatility and outperforms estimators using historical data to predict realised volatility (RV). Moreover, such exclusive can be replicated across various asset types (Andersen et al. 2000).

Previous research on currency options is mainly based on daily data to calculate IV. The IV was found to forecast volatility effectively for the horizon of up to six to nine months and capture almost 50 per cent of actual volatility in Scott and Tucker's research (Scott and Tucker 1989). They used the data sample of five major currency options, including the Canadian dollar (CAD), British pound (GBP), Swiss franc (CHF), Deutsche mark (DEM) and Japanese yen (JPY). However, no evidence of improved predictive accuracy was found when the investor's information set included historical volatility. Xu and Taylor (1994) examined the informational efficiency of the four currency options (GBP/USD, DEM/USD, JPY/USD and CHF/USD) traded on the Philadelphia Stock Exchange for seven years since 1985. Their findings showed that valuable information about future volatilities could be extracted from option prices. Jorion (1995) compared the predictive power of IV with the historical volatility using the dataset of three currency options (DEM, JPY and CHF) obtained from the Chicago Mercantile Exchange (CME). They concluded that IV forecast capability exceeded historical time-series volatility models. Kazantzis and Tessaromatis (2001) reported similar findings for forecast horizons covering from one day to three months maturity currency options JPY, DEM, GBP, CHF, CAD and AUD against the USD for more than seven years period from 1989.

The IV of the CAD, CHF, DEM, GBP and JPY options was low in the early part of the week but remained high in the rest of the week that started on Wednesdays (Kim and Kim 2003). Further, the IV subsumed the required information to forecast actual volatility for either one month or three months horizon using the data sample consisting of DEM, GBP and JPY options (Pong et al. 2004). According to Christoffersen and Mazzotta (2005), ATM (at the money) IV options based on EUR, GBP, and JPY were relatively reliable and unbiased predictions of the actual volatility for the forecast horizon of one and three months. The IV based on the Brazilian options contained vital information missing in the economic models that could produce superior FX forecasts (Chang and Tabak 2007).

IV subsumed the required information to forecast volatility, and an unbiased forecast estimator for the FX market has introduced IV (Busch et al. 2011). Further, the predictive power of IV was far superior to GARCH volatility for low and high fluctuation of the FX market (Pilbeam and Langeland 2015). The IV also incorporated all the information about future volatility of historical volatility (Sahoo and Trivedi 2018). The IV based on the at-the-money CHF, EUR, GBP and JPY options decreased on the announcement day (Marshall et al. 2012). Currency options IV provided an early warning of a crisis (John and Themba 2012). The information from the volatility smile of one-month maturity IV can improve the FX volatility forecast accuracy (Wong and Heaney 2017).

Most of the previous studies on currency options employed the daily IV to forecast FX's volatility. However, the use of IV for pricing options has not been explored in deep. Technology development has led to the emergence of high-frequency data that contain a massive amount of information for trading improvement; however, very little research analysing the potential of big data in estimating currency options prices for decision making. Thus, our study will fill this gap by applying the high-frequency data in calculating IV to forecasting volatility and estimating currency options prices.

3. Discussion

In the following section, we offer an outline of the approaches used to interpret the use of high-frequency data in estimating and forecasting underlying asset volatility and options prices. The study divides the research methodology into five sub-sections, (i) calculate IV, (ii) compute RV, (iii) IV forecasting RV, (iv) IV calculating options model price and (v) measuring the options pricing error.

3.1. Implied Volatility Calculation

The literature usually employs the BSM model for pricing European currency options (Corredor and Santamaría 2004). Ease of calculation and theoretical approximations between conditional volatility of BSM for ATM closest-to-expiration options and stochastic volatility are among the main explanations for their general use (Fleming 1998; Nelson 1991). The following notations with descriptions are for the BS model.

C_t = call options price in domestic currency at time t;
P_t = put options price in domestic currency at time t;
S_t = FX spot rate at time t;
X_t = options strike price in domestic currency at time t;
R_t^d = interest rate of domestic currency at time t;
R_t^f = interest rate of foreign currency at time t;
T = time to options expiry;
σ_t = underlying currency volatility;
N = function for the cumulative normal distribution.

For the BSM model, the price of the European-style call and put options are obtained as:

$$C_t = S_t e^{-R_t^f T} N(d_{1,t}) - X_t e^{-R_t^d} N(d_{2,t}), \tag{1}$$

$$P_t = X_t e^{-R_t^d T} N(-d_{2,t}) - S_t e^{-R_t^f} N(-d_{1,t}), \tag{2}$$

$$d_{1,t} = \frac{ln\left(\frac{S_t}{X_t}\right) + \left(R_t^d - R_t^f + \frac{\sigma_t^2}{2}\right)T}{\sigma_t\sqrt{T}} \text{ and } d_{2,t} = \frac{ln\left(\frac{S_t}{X_t}\right) + \left(R_t^d - R_t^f - \frac{\sigma_t^2}{2}\right)T}{\sigma_t\sqrt{T}} = d_{1,t} - \sigma_t\sqrt{T}.$$

For notations convenience, let $\xi_t = e^{-R_t^f T}$ and $\eta_t = e^{-R_t^d T}$ to rewrite Equations (1) and (2) as follows:

$$C_t^{mkt,k,l} = S_t\xi_t N\left[d_{1,t}\left(\sigma_{c,t}^{k,l,g}\right)\right] - X_t\eta_t N\left[d_{2,t}\left(\sigma_{c,t}^{k,l,g}\right)\right] \tag{3}$$

$$P_t^{mkt,k,l} = X_t\eta_t N\left[-d_{2,t}\left(\sigma_{p,t}^{k,l,h}\right)\right] - S_t\xi_t N\left[-d_{1,t}\left(\sigma_{p,t}^{k,l,h}\right)\right] \tag{4}$$

where $\forall_{mkt}=$ call options and put options price, $\forall_k=$ options maturity for one, two and three months, $\forall_1=$ opening, midday and closing options period for a trading day, $\forall_g=$ IV_CHFC (IV based on the Swiss franc call options price), IV_EURC (IV based on the Euro call options price), IV_GBPC (IV based on the British pound call options price), $\forall_h=$ IV_CHFP (IV based on the Swiss franc put options price), IV_EURP (IV based on the Euro put options price) and IV_GBPP (IV based on the British pound put options price). The IV for the ATM-call options market price $\left(\sigma_{c,t}^{k,l,g}\right)$ and IV for the ATM-put options market price $\left(\sigma_{p,t}^{k,l,h}\right)$ are computed by Newton-Raphson's iterative search procedure (Press et al. 1992).

This study follows the method introduced by Jorion (1995), which calculated IV by averaging the IV obtained using the price of call options and put options price as in Equation (5):

$$\hat{\sigma}_t^{k,l,m} = \frac{\hat{\sigma}_{c,t}^{k,l,g} + \hat{\sigma}_{p,t}^{k,l,h}}{2} \tag{5}$$

where $\forall_m=$ IV_CHF (Swiss franc options implied volatility), IV_EUR (implied volatility for Euro options) and IV_GBP (British pound options implied volatility).

3.2. Realised Volatility Computation

RV is calculated by adding the squared intraday returns sampled at a given recurrence rate (Andersen and Bollerslev 1998; Barndorff-Nielsen and Shephard 2002). No optimal frequency to construct RV has been evidenced. However, the five minutes interval RV used as the benchmark outperformed other measures, as evidenced in practice and previous literature (Liu et al. 2015). Therefore, unobservable actual volatility is represented by daily RV calculated from five minutes intervals intraday spot prices. If the spot price is S_i for a five-minute sampling frequency, the foreign exchange rate return in a five minutes intervals is calculated as:

$$r_{i,t} = ln\left(\frac{S_i}{S_{i-1}}\right), \quad (6)$$

where $r_{i,t}$ is the return of spot price, and i is the interval on day t. Equation (7) computes the realised variance of day t,

$$v_t = \sum_{i=1}^{n} r_{t,i}^2, \quad (7)$$

where n represents the total number of intervals during the trading hour of currency options from 9:30 to 16:00 of the trading day (Monday to Friday). Further, RV is estimated as the standard deviation of the realised variance. Therefore, the RV per trading day is:

$$\hat{\sigma}_t^{RV} = \sqrt{v_t} \quad (8)$$

Finally, the exchange is closed days are ignored, and the RV per annum is calculated by considering only intraday data of trading days as in Equation (9).

$$\hat{\sigma}_t^{RV,q} = \sqrt{Dv_t} \quad (9)$$

where D represents 252 trading days per year, consistent with the usual assumption of the options market. In Equation (9), $\forall_q =$ RV_CHF (realised volatility for Swiss franc spot rate), RV_EUR (realised volatility for Euro spot rate) and RV_GBP (realised volatility for British pound spot rate).

3.3. Implied Volatility Forecasts Realised Volatility

The forecasting assessment is undertaken using the regression analysis proposed by Mincer and Zarnowitz (1969). It is also known as the Mincer-Zarnowitz (MZ) regression. Under the MZ regression analysis, as in Equation (10), the estimated RV is regressed on a constant and IV.

$$\hat{\sigma}_t^{RV,q} = \beta_0 + \beta_1 \hat{\sigma}_{t-j}^{k,l,m} + \varepsilon_t \quad (10)$$

where, $\forall_j =$ within-a-week forecast horizon; one-week forecast horizon; one-month forecast horizon. For the within-a-week horizon, the IV is computed 1 to 4 days earlier than the RV is estimated. Similarly, the one-week horizon implies that the IV is estimated one week before the date of RV is calculated. Further, the one-month horizon considers that the IV is calculated one month earlier than the date of RV is estimated.

The MZ regression analysis conducts two different aspects of the volatility forecast. First, examining the intercept (β_0) and slope (β_1) by a joint hypothesis (H_0: $\beta_0 = 0$ and $\beta_1 = 1$) to assess the predictability, unbiasedness and efficiency (Guler et al. 2017). Second, R-squared (R^2) examine the forecast accuracy as it represents the high goodness of fit value. Therefore, R^2 is the statistical measure that represents the RV variance percentage explained by IV. It also compares the forecasting capability of intraday IV based on the different time to maturity to predict RV within a week, one-week and one-month horizons. For the closing price, one month to maturity for the one-week horizon, the R^2 of IV is higher than that of IV at the opening price. It suggests that the IV at the closing price for the one-week horizon can explain well RV; IV based on the closing price outperforms the opening IV in RV forecast for the one week. The MZ regression analysis with Newey-West corrected errors for heteroscedasticity, and serial correlation employs the OLS (ordinary least squared) method.

3.4. Implied Volatility Estimating Options Model Price

The estimated IV is then employed as the BSM options pricing model's input to compute the call model price and put model price. The $C_t^{mkt,k,l}$ and $P_t^{mkt,k,l}$ in Equations (3) and (4) is substituted with call options model price ($\prod_{c,t}^{mod,k,l}$) and put options model price ($\prod_{p,t}^{mod,k,l}$), as in Equations (11) and (12), respectively.

$$\prod_{c,t}^{mod,k,l} = S_t \xi_t N\left[d_{1,t}\left(\hat{\sigma}_{t-j}^{k,l,m}\right)\right] - X_t \eta_t N\left[d_{2,t}\left(\hat{\sigma}_{t-j}^{k,l,m}\right)\right] \quad (11)$$

$$\prod_{p,t}^{mod,k,l} = X_t \eta_t N\left[-d_{2,t}\left(\hat{\sigma}_{t-j}^{k,l,m}\right)\right] - S_t \xi_t N\left[-d_{1,t}\left(\hat{\sigma}_{t-j}^{k,l,m}\right)\right] \quad (12)$$

3.5. Options Pricing Error Estimation

The options pricing error (OPE) is defined as the difference between the ATM options and the estimated options model price. The minimum OPE is estimated using standard statistical accuracy criteria. They consist of mean absolute error (MAE), mean squared error (MSE), and the root mean squared error (RMSE), as in Equations (13)–(15), respectively.

$$MAE_u^{m,k,l} = \frac{1}{n}\sum_{t=1}^{n}\left|\Pi_{u,t}^{ATM,k,l} - \hat{\Pi}_{u,t}^{mod,k,l}\right| \quad (13)$$

$$MSE_u^{m,k,l} = \frac{1}{n}\sum_{t=1}^{n}\left(\Pi_{u,t}^{ATM,k,l} - \hat{\Pi}_{u,t}^{mod,k,l}\right)^2 \quad (14)$$

$$MAPE_u^{m,k,l} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left|\frac{\Pi_{u,t}^{ATM,k,l} - \hat{\Pi}_{u,t}^{mod,k,l}}{\Pi_{u,t}^{ATM,k,l}}\right|} \quad (15)$$

where $\forall_u =$ call price, put price.

3.6. Data Description

We used quotations of European currency options CHF, EUR, and GBP from the Options Price Reporting Authority (OPRA). Thomson Reuters' database provided data through the Securities Industry Research Centre of Asia-Pacific (SIRCA). For all currencies, the data collection spans from 1 January 2010 to 31 December 2020. The options trading period is from 9:30 a.m. to 4:00 p.m. (US Eastern standard time), Monday through Friday, except on public holidays. These options are expired on the third Friday of each month. The contract sizes for the CHF, EUR and GBP options were CHF10,000, EUR10,000, and GBP10,000, respectively, and settled in USD. The number of calendar days from the trading date to the expiry date of options was considered to be the time to maturity. The 2–30 days, 31–60 days and 61–90 days are considered as one month, two months and three months options maturity, respectively. Further, 9:30 to 10:00, 12:30 to 13:00 and 15:30 to 16:00 were opening, midday and closing periods for calculating the intraday IV. The two and a half hours' time difference between the 'opening period' and 'midday period' and between the 'midday period' and 'closing period' was distributed equally during trading day hours. The constant variance assumption of the BSM model estimates the IV with a biasedness. However, we measured IV using ATM options since model bias was the smallest for near-the-money options (Hull and White 1987).

In Xing et al. (2010) study, the ATM measure in the strike price to the stock price ratio is between 0.95 and 1.05. To reduce the bid/ask bounce issues, we computed options price as the average of each five-minute interval's close bid/ask quote (Blair et al. 2001). The CHF, EUR, GBP and USD one-month, two-month and three-month deposit interest rates were used as the proxy of risk-free interest rates.

4. Empirical Analysis and Results

For the within-a-week forecast horizon, Table 1 describes the performance of IV_CHF, IV_EUR and IV_GBP in predicting RV_CHF, RV_EUR and RV_GBP, respectively. The closing price of the one-month, two months, and three months maturity IV_CHF outperformed others in predicting the RV_CHF (with the values of R^2 are 0.354, 0.346, 0.321, respectively) with the best performance of IV was reported on Thursday.

Next, the Tuesday closing price of one-month, two-month and three-month maturity IV_EUR were superior to forecast RV_EUR (R^2 = 0.154, 0.237, 0.223, respectively). Finally, the Thursday closing price of one-month, and two-month maturity IV_GBP outperformed in predicting RV_GBP (R^2 = 0.376 and 0.279, respectively). Therefore, overall results for the within-a-week horizon forecast suggested that the closing price of one-month maturity IV_CHF (R^2 = 0.354) and IV_GBP (R^2 = 0.376) on Thursday (end-week day) were superior to forecast RV_CHF and RV_GBP, respectively. However, the two-month maturity IV_EUR (with a value of R^2 = 0.237) on Tuesday (begin-week day), in the closing period, showed the best performance in forecasting the RV_EUR.

Table 1. IV forecast RV for within-week forecast horizon.

Within-Week Forecast Horizon	IV_CHF Forecast RV_CHF						IV_EUR Forecast RV_EUR						IV_GBP Forecast RV_GBP					
	1-Month Maturity		2-Month Maturity		3-Month Maturity		1-Month Maturity		2-Month Maturity		3-Month Maturity		1-Month Maturity		2-Month Maturity		3-Month Maturity	
	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2
Panel A: Opening period (9:30–10:00)																		
Mon to Fri	0.264	0.212	0.416	0.158	0.612	0.115	0.202	0.138 [2]	0.387	0.220 [2]	0.421	0.215 [2]	0.196	0.322	0.330	0.229	0.600	0.128
Tue to Fri	0.378	0.203	0.625	0.202	0.612	0.201	0.156	0.072	0.391	0.176	0.441	0.187	0.221	0.346	0.320	0.190	0.740	0.146
Wed to Fri	0.351	0.229	0.575	0.213	0.617	0.202	0.221	0.129	0.440	0.179	0.484	0.201	0.197	0.333	0.415	0.246	0.720	0.139
Thu to Fri	0.362	0.334 [1]	0.601	0.314 [2]	0.656	0.225 [1]	0.239	0.124	0.371	0.172	0.412	0.154	0.321	0.360 [2]	0.530	0.265 [2]	0.730	0.252 [3]
Panel B: Midday period (12:30–13:00)																		
Mon to Fri	0.304	0.167	0.425	0.153	0.557	0.143	0.184	0.116	0.345	0.179	0.305	0.162	0.212	0.266	0.329	0.200	0.474	0.163
Tue to Fri	0.268	0.185	0.368	0.173	0.545	0.152	0.201	0.134 [1]	0.316	0.192 [1]	0.306	0.179 [1]	0.186	0.256	0.318	0.205	0.460	0.151
Wed to Fri	0.236	0.184	0.419	0.182	0.534	0.176	0.162	0.084	0.335	0.145	0.386	0.168	0.217	0.279 [1]	0.400	0.245 [1]	0.485	0.189 [2]
Thu to Fri	0.361	0.343 [2]	0.553	0.265 [1]	0.614	0.272 [2]	0.209	0.129	0.328	0.162	0.354	0.142	0.212	0.215	0.360	0.201	0.440	0.151
Panel C: Closing period (15:30–16:00)																		
Mon to Fri	0.278	0.176	0.389	0.167	0.541	0.158	0.200	0.120	0.329	0.164	0.342	0.143	0.221	0.289	0.360	0.266	0.515	0.161
Tue to Fri	0.292	0.202	0.502	0.245	0.602	0.212	0.195	0.154 [3]	0.375	0.237 [3,*]	0.352	0.234 [3]	0.201	0.275	0.370	0.236	0.500	0.160
Wed to Fri	0.281	0.221	0.501	0.218	0.590	0.213	0.211	0.115	0.356	0.153	0.372	0.154	0.186	0.277	0.415	0.207	0.496	0.169
Thu to Fri	0.295	0.354 [3,*]	0.592	0.346 [3]	0.694	0.321 [3]	0.259	0.112	0.359	0.178	0.414	0.178	0.237	0.376 [3,*]	0.430	0.279 [3]	0.495	0.178 [1]

Note: The implied volatility based on Swiss franc (CHF), Euro (EUR) and British pound (GBP) options is denoted by IV_CHF, IV_EUR, and IV_GBP. IV_CHF, IV_EUR, and IV_GBP are computed using Equation (5) based on one-month (options expire in 2 to 30 days), two-month (options expire in 31 to 60 days), and three-month (options expire in 61 to 90 days) maturity options of CHF, EUR, and GBP, respectively, for the opening (options trading period between 9:30 and 10:00), midday (options trading period between 12:30 and 13:00), and closing (options trading period between 15:30 and 16:00) a trading day. The realised volatility of the Swiss franc, Euro, and the British pound is represented by RV_CHF, RV_EUR, and RV_GBP, respectively. RV_CHF, RV_EUR, and RV_GBP are calculated using Equation (9) based on the CHF, EUR and GBP spot rate, respectively, obtaining a 5 min frequency. The slope coefficient and R^2 of the within-week forecast horizon (using the IV of Monday, Tuesday, Wednesday, and Thursday to forecast the RV on Friday of the same week) are estimated by Equation (10) under the MZ. The *p*-value does not report in the table to avoid repetitions since *p*-values are zero for all cases. The lower, mid and higher values of highest R^2 for the opening, midday, and closing trading periods are denoted by the superscript [1], [2], and [3], respectively. The highest value of R^2 for IV based on different maturities is represented by *. The begin-week day is Monday or Tuesday, the mid-week is Wednesday, and the end-week is Thursday.

For the one-week forecast horizon, Table 2 shows the IV_CHF, IV_EUR and IV_GBP forecasting capability to predict RV_CHF, RV_EUR and RV_GBP, respectively. The Tuesday closing price of one-month maturity IV_CHF (with the value of R^2 = 0.469) performed better in forecasting RV_CHF. However, the Tuesday opening price of two-month and three-month maturity IV_CHF (with a value of R^2 = 0.360 and 0.363, respectively) performed better when forecasting RV_CHF. For EUR, the Monday closing price of one-month maturity IV_EUR (with a value of R^2 = 0.430) showed a better performance when predicting RV_EUR. However, Monday opening price of two-month and three-month maturity IV_EUR were superior in forecasting RV_EUR (R^2 = 0.348 and 0.218, respectively). The similar pattern was reported for GBP. The Monday closing price of one-month maturity IV_GBP and opening price of two-month and three-month maturity IV_GBP dominated in pricing RV_GBP. Therefore, overall results for the one-week horizon revealed that one-month maturity IV_CHF (with a value of $R^2 = 0.469$), IV_EUR (with a value of $R^2 = 0.430$) and IV_GBP (with a value of $R^2 = 0.450$) in the closing period of Monday or Tuesday (trading day at the beginning of the week) held superior forecasting ability when predicting RV_CHF, RV_EUR and RV_GBP, respectively.

Table 2. IV forecast RV for the one-week horizon.

One-Week Forecast Horizon	IV_CHF Forecast RV_CHF						IV_EUR forecast RV_EUR						IV_GBP forecast RV_GBP					
	1-Month Maturity		2-Month Maturity		3-Month Maturity		1-Month Maturity		2-Month Maturity		3-Month Maturity		1-Month Maturity		2-Month Maturity		3-Month Maturity	
	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2
Panel A: Opening period (9:30–10:00)																		
Mon to Mon	0.270	0.377	0.380	0.239	0.601	0.183	0.210	0.410 [2]	0.375	0.348 [3]	0.505	0.218 [3]	0.195	0.440 [2]	0.352	0.390 [3]	0.470	0.352 [3]
Tue to Tue	0.391	0.440 [2]	0.540	0.360 [3]	0.740	0.363 [3]	0.185	0.385	0.400	0.339	0.470	0.215	0.200	0.375	0.370	0.320	0.520	0.220
Wed to Wed	0.315	0.325	0.435	0.274	0.630	0.242	0.190	0.275	0.415	0.285	0.475	0.140	0.150	0.350	0.360	0.275	0.500	0.170
Thu to Thu	0.370	0.212	0.600	0.266	0.590	0.231	0.265	0.150	0.367	0.140	0.400	0.156	0.390	0.370	0.510	0.255	0.670	0.300
Fri to Fri	0.425	0.352	0.550	0.238	0.675	0.220	0.175	0.190	0.451	0.175	0.460	0.090	0.435	0.300	0.360	0.250	0.520	0.270
Panel B: Midday period (12:30–13:00)																		
Mon to Mon	0.278	0.285	0.367	0.239	0.525	0.224	0.190	0.370 [1]	0.320	0.312 [1]	0.390	0.205 [1]	0.200	0.385	0.300	0.320	0.400	0.240
Tue to Tue	0.279	0.380 [1]	0.424	0.340 [1]	0.580	0.274 [1]	0.195	0.325	0.330	0.292	0.395	0.201	0.160	0.430 [1]	0.310	0.338 [1]	0.420	0.250 [1]
Wed to Wed	0.190	0.268	0.396	0.217	0.480	0.074	0.175	0.315	0.375	0.293	0.380	0.165	0.180	0.380	0.305	0.285	0.425	0.235
Thu to Thu	0.280	0.016	0.550	0.008	0.615	0.007	0.220	0.110	0.300	0.110	0.350	0.102	0.315	0.255	0.370	0.200	0.475	0.200
Fri to Fri	0.353	0.186	0.430	0.164	0.525	0.162	0.192	0.135	0.318	0.140	0.370	0.089	0.300	0.310	0.280	0.195	0.500	0.200
Panel C: Closing period (15:30–16:00)																		
Mon to Mon	0.253	0.211	0.390	0.252	0.528	0.212	0.210	0.430 [3,*]	0.321	0.315 [2]	0.440	0.210 [2]	0.215	0.450 [3,*]	0.380	0.385 [2]	0.450	0.285 [2]
Tue to Tue	0.266	0.469 [3,*]	0.440	0.359 [2]	0.585	0.289 [2]	0.185	0.350	0.354	0.312	0.430	0.170	0.190	0.425	0.340	0.370	0.440	0.240
Wed to Wed	0.225	0.251	0.390	0.225	0.515	0.166	0.182	0.282	0.332	0.268	0.430	0.150	0.150	0.370	0.315	0.300	0.420	0.170
Thu to Thu	0.198	0.012	0.470	0.005	0.660	0.004	0.280	0.160	0.375	0.135	0.425	0.160	0.280	0.300	0.415	0.240	0.510	0.225
Fri to Fri	0.334	0.250	0.490	0.175	0.590	0.137	0.250	0.170	0.369	0.150	0.420	0.130	0.330	0.335	0.320	0.230	0.550	0.280

Note: The implied volatility based on Swiss franc (CHF), Euro (EUR) and British pound (GBP) options is denoted by IV_CHF, IV_EUR, and IV_GBP. IV_CHF, IV_EUR, and IV_GBP are computed using Equation (5) based on one-month (options expire in 2 to 30 days), two-month (options expire in 31 to 60 days), and three-month (options expire in 61 to 90 days) maturity options of CHF, EUR, and GBP, respectively, for the opening (options trading period between 9:30 and 10:00), midday (options trading period between 12:30 and 13:00), and closing (options trading period between 15:30 and 16:00) a trading day. The realised volatility of the Swiss franc, Euro, and the British pound is represented by RV_CHF, RV_EUR, and RV_GBP, respectively. RV_CHF, RV_EUR, and RV_GBP are calculated using Equation (9) based on the CHF, EUR and GBP spot rate, respectively, obtaining a 5 min frequency. The slope coefficient and R^2 of the one-week forecast horizon (using the IV of Monday, Tuesday, Wednesday, and Thursday to forecast the RV of Monday, Tuesday, Wednesday, Thursday, and Friday of next week) are estimated by Equation (10) under the MZ. The *p*-value does not report in the table to avoid repetitions since *p*-values are zero for all cases. The lower, mid and higher values of highest R^2 for the opening, midday, and closing trading periods are denoted by the superscript [1], [2], and [3], respectively. The highest value of R^2 for IV based on different maturities is represented by *. The begin-week day is Monday or Tuesday, the mid-week is Wednesday, and the end-week.

For the one-month forecast horizon, Table 3 shows the performance of IV_CHF, IV_EUR and IV_GBP in forecasting RV_CHF, RV_EUR and RV_GBP, respectively. The opening pricie of one-month ($R^2 = 0.300$) and three-month ($R^2 = 0.220$) maturity IV_CHF on Tuesday performed better in forecasting RV_CHF. However, the Tuesday closing price of two-month maturity IV_CHF held higher predictive power. Next, the Monday opening price of one-month ($R^2 = 0.255$) and three-month ($R^2 = 0.305$) maturity IV_EUR was superior when predicting RV_EUR. The Monday closing price of two-month maturity IV_EUR ($R^2 = 0.390$) performed better when forecasting RV_EUR. Finally, the Monday opening price of one-month and three-month maturity IV_GBP ($R^2 = 0.270$ and $R^2 = 0.360$, repectively) outperformed when predicting RV_GBP. The Monday closing price of two-month maturity IV_GBP performed better when forecasting RV_GBP ($R^2 = 0.400$). Overall results for the one-month horizon forecast suggested that the two-month maturity IV_CHF ($R^2 = 0.330$), IV_EUR ($R^2 = 0.390$) and IV_GBP ($R^2 = 0.400$) in the closing periods of Monday or

Tuesday (begin-week day) held higher forecasting capabilities in predicting RV_CHF, RV_EUR, and RV_GBP, respectively.

Table 3. IV forecast RV for one-month forecast horizon.

One-Month Forecast Horizon	IV_CHF Forecast RV_CHF						IV_EUR Forecast RV_EUR						IV_GBP Forecast RV_GBP					
	1-Month Maturity		2-Month Maturity		3-Month Maturity		1-Month Maturity		2-Month Maturity		3-Month Maturity		1-Month Maturity		2-Month Maturity		3-Month Maturity	
	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2
Panel A: Opening period (9:30–10:00)																		
Mon to Mon	0.270	0.230	0.274	0.215	0.460	0.200	0.225	0.255 [3]	0.350	0.380 [2]	0.401	0.305 [3]	0.255	0.270 [3]	0.400	0.390 [2]	0.500	0.360 [3]
Tue to Tue	0.340	0.300 [3]	0.400	0.310 [2]	0.550	0.220 [3]	0.145	0.200	0.345	0.374	0.460	0.280	0.165	0.170	0.305	0.280	0.545	0.250
Wed to Wed	0.288	0.220	0.410	0.250	0.530	0.205	0.250	0.245	0.410	0.310	0.465	0.290	0.140	0.130	0.340	0.225	0.450	0.225
Thu to Thu	0.275	0.160	0.330	0.105	0.400	0.060	0.170	0.055	0.330	0.101	0.330	0.090	0.370	0.180	0.490	0.280	0.455	0.215
Fri to Fri	0.290	0.140	0.410	0.150	0.525	0.150	0.180	0.060	0.300	0.180	0.450	0.015	0.380	0.101	0.400	0.270	0.465	0.200
Panel B: Midday period (12:30–13:00)																		
Mon to Mon	0.213	0.120	0.285	0.160	0.400	0.150	0.170	0.175	0.300	0.280 [1]	0.360	0.250	0.150	0.190 [1]	0.290	0.320 [1]	0.370	0.300 [1]
Tue to Tue	0.222	0.200 [2]	0.360	0.240 [1]	0.460	0.205 [2]	0.185	0.200 [2]	0.320	0.310	0.390	0.280 [1]	0.120	0.120	0.285	0.355	0.380	0.270
Wed to Wed	0.220	0.170	0.330	0.172	0.421	0.170	0.185	0.170	0.330	0.240	0.385	0.250	0.160	0.180	0.290	0.300	0.370	0.260
Thu to Thu	0.010	0.003	0.270	0.100	0.475	0.080	0.160	0.065	0.290	0.102	0.330	0.085	0.300	0.135	0.350	0.230	0.480	0.220
Fri to Fri	0.230	0.075	0.290	0.090	0.330	0.083	0.170	0.050	0.300	0.090	0.300	0.090	0.202	0.085	0.310	0.200	0.390	0.170
Panel C: Closing period (15:30–16:00)																		
Mon to Mon	0.216	0.150	0.290	0.180	0.410	0.155	0.180	0.190 [1]	0.320	0.390 [3,*]	0.380	0.290 [2]	0.250	0.200 [2]	0.320	0.400 [3,*]	0.400	0.340 [2]
Tue to Tue	0.220	0.190 [1]	0.330	0.330 [3,*]	0.450	0.185 [1]	0.190	0.120	0.330	0.300	0.400	0.260	0.150	0.150	0.310	0.365	0.520	0.310
Wed to Wed	0.175	0.120	0.310	0.160	0.400	0.150	0.200	0.160	0.300	0.190	0.350	0.180	0.162	0.180	0.305	0.290	0.502	0.280
Thu to Thu	0.085	0.002	0.260	0.100	0.505	0.090	0.225	0.070	0.310	0.115	0.365	0.110	0.300	0.175	0.380	0.265	0.401	0.240
Fri to Fri	0.200	0.062	0.300	0.090	0.400	0.080	0.230	0.069	0.300	0.120	0.340	0.100	0.285	0.095	0.380	0.230	0.475	0.210

Note: The implied volatility based on Swiss franc (CHF), Euro (EUR) and British pound (GBP) options is denoted by IV_CHF, IV_EUR, and IV_GBP. IV_CHF, IV_EUR, and IV_GBP are computed using Equation (5) based on one-month (options expire in 2 to 30 days), two-month (options expire in 31 to 60 days), and three-month (options expire in 61 to 90 days) maturity options of CHF, EUR, and GBP, respectively, for the opening (options trading period between 9:30 and 10:00), midday (options trading period between 12:30 and 13:00), and closing (options trading period between 15:30 and 16:00) a trading day. The realised volatility of the Swiss franc, Euro, and the British pound is represented by RV_CHF, RV_EUR, and RV_GBP, respectively. RV_CHF, RV_EUR, and RV_GBP are calculated using Equation (9) based on the CHF, EUR and GBP spot rate, respectively, obtaining a 5 min frequency. The slope coefficient and R^2 of the one-week forecast horizon (using the IV of Monday, Tuesday, Wednesday, and Thursday to forecast the RV of Monday, Tuesday, Wednesday, Thursday, and Friday of next month) are estimated by Equation (10) under the MZ. The *p*-value does not report in the table to avoid repetitions since *p*-values are zero for all cases. The lower, mid and higher values of highest R^2 for the opening, midday, and closing trading periods are denoted by the superscript [1, 2], and [3], respectively. The highest value of R^2 for IV based on different maturities is represented by *. The begin-week day is Monday or Tuesday, the mid-week is Wednesday, and the end-week.

In the majority of cases, the closing IV outperformed in predicting RV for all tested forecast horizons. Therefore, the currency options price is estimated in this study by employing input IV based on closing period options with one-month, two-month and three-month maturity. Next, IV_CHF, IV_EUR and IV_GBP, based on the closing period traded options, were used as inputs for Equations (11) and (12) to calculate the call options model price and put options model price, respectively. Finally, Equations (13)–(15) employ MAE, MSE and MAPE methods, respectively, to measure the options pricing error (OPE).

Table 4 describes the performance of IV_CHF, IV_EUR and IV_GBP to price the CHF, EUR and GBP options, respectively, for the within-week horizon. The MSE measure showed that the Monday one-month (with call pricing error = 0.094 and put pricing error = 0.021), two-month (with call pricing error = 0.080 and put pricing error = 0.020), and three-month (with call pricing error = 0.082 and put pricing error = 0.025) maturity IV_CHF outperformed for pricing CHF call options and put options. Similarly, the one-month (with call pricing error = 0.065 and put pricing error = 0.025), two-month (with call pricing error = 0.060 and put pricing error = 0.030) and three-month (with call pricing error = 0.090 and put pricing error = 0.030) maturity IV_EUR on Monday was superior to price

EUR call options, and EUR put options. Finally, the one-month (with call pricing error = 0.030 and put pricing error = 0.025), two-month (with call pricing error = 0.071 and put pricing error = 0.025), and three-month (with call pricing error = 0.070 and put pricing error = 0.020) maturity IV_GBP of Thursday held appropriate information to compute GBP call options price and GBP put options price. In summary, the two-month maturity options of Monday (begin weekday) IV_CHF (with call pricing error = 0.080 and put pricing error = 0.020) and IV_EUR (with call pricing error = 0.060 and put pricing error = 0.030) contained appropriate information for pricing CHF and GBP options, respectively. However, Thursday's one-month maturity options (end-week day) IV_GBP (with call pricing error = 0.030 and put pricing error = 0.025) held vital information in estimating the GBP options price.

Table 4. Estimate options pricing error for the within-week horizon.

Within-Week Estimate Horizon	Options	IV_CHF			IV_EUR			IV_GBP		
		1-Month Maturity	2-Month Maturity	3-Month Maturity	1-Month Maturity	2-Month Maturity	3-Month Maturity	1-Month Maturity	2-Month Maturity	3-Month Maturity
Panel A: Pricing error under MAE measure										
Mon to Fri	CALL	0.180 [2]	0.180 [2]	0.215 [2]	0.170 [2]	0.170 [2]	0.230 [2]	0.120	0.250	0.210
	PUT	0.010 [2]	0.100 [2]	0.110 [2]	0.100 [2]	0.090 [2]	0.125 [2]	0.100	0.100	0.115
Tue to Fri	CALL	0.300	0.260	0.290	0.290	0.275	0.260	0.200	0.210	0.210
	PUT	0.135	0.110	0.130	0.145	0.120	0.140	0.110	0.110	0.120
Wed to Fri	CALL	0.250	0.185	0.300	0.200	0.270	0.244	0.210	0.222	0.210
	PUT	0.210	0.100	0.135	0.130	0.115	0.135	0.110	0.118	0.115
Thu to Fri	CALL	0.255	0.250	0.290	0.270	0.180	0.250	0.080 [2]	0.200 [2]	0.200 [2]
	PUT	0.135	0.125	0.130	0.130	0.100	0.140	0.092 [2]	0.093 [2]	0.102 [2]
Panel B: Pricing error under MSE measure										
Mon to Fri	CALL	0.094 [3]	0.080 [3,*]	0.082 [3]	0.065 [3]	0.060 [3,*]	0.090 [3]	0.075	0.092	0.080
	PUT	0.021 [3]	0.020 [3,*]	0.025 [3]	0.025 [3]	0.030 [3,*]	0.030 [3]	0.030	0.030	0.030
Tue to Fri	CALL	0.150	0.020	0.100	0.170	0.150	0.140	0.065	0.080	0.075
	PUT	0.060	0.050	0.050	0.045	0.035	0.033	0.029	0.032	0.030
Wed to Fri	CALL	0.145	0.090	0.160	0.080	0.115	0.122	0.073	0.080	0.090
	PUT	0.030	0.030	0.050	0.027	0.036	0.040	0.034	0.035	0.045
Thu to Fri	CALL	0.155	0.140	0.180	0.150	0.070	0.126	0.030 [3,*]	0.071 [3]	0.070 [3]
	PUT	0.090	0.050	0.060	0.050	0.038	0.040	0.025 [3,*]	0.025 [3]	0.020 [3]
Panel C: Pricing error under MAPE measure										
Mon to Fri	CALL	0.201 [1]	0.225 [1]	0.220 [1]	0.175 [1]	0.185 [1]	0.250 [1]	0.140	0.260	0.220
	PUT	0.125 [1]	0.125 [1]	0.135 [1]	0.150 [1]	0.120 [1]	0.135 [1]	0.120	0.130	0.125
Tue to Fri	CALL	0.320	0.275	0.298	0.310	0.280	0.292	0.210	0.221	0.231
	PUT	0.154	0.145	0.156	0.172	0.135	0.140	0.155	0.135	0.140
Wed to Fri	CALL	0.275	0.260	0.310	0.225	0.275	0.264	0.250	0.250	0.235
	PUT	0.225	0.130	0.175	0.154	0.155	0.158	0.135	0.140	0.145
Thu to Fri	CALL	0.310	0.271	0.367	0.281	0.200	0.260	0.120 [1]	0.215 [1]	0.205 [1]
	PUT	0.195	0.185	0.183	0.153	0.135	0.152	0.110 [1]	0.125 [1]	0.090 [1]

Note: The implied volatility of Swiss franc (CHF), Euro (EUR) and British pound (GBP) options are represented by IV_CHF, IV_EUR, and IV_GBP, respectively. The closing period IV_CHF, IV_EUR, and IV_GBP is computed using one-month (options trading days between 2 and 30), two-month (options trading days between 31 and 60), and three-month (options trading days between 61 and 90) maturity CHF, EUR, and GBP options are used to estimate call and put price by Equations (11) and (12), respectively. The MAE, MSE, and MAPE methods are employed by Equations (13)–(15), respectively, to measure the closing OPE. The OPE under MAE, MSE and MAPE measures are given in panels A, B, and C, respectively, for a within-a-week estimate horizon (that is, IV of Monday, Tuesday, Wednesday, and Thursday to forecast option price on Friday of the same week). The higher, mid, and lower pricing errors are denoted by superscripts [1, 2], and [3], respectively, among MAE, MSE, and MAPE measures for each option for one month, two-month and three-month maturity. The smallest pricing error is represented by * for one-month, two-month, and three-month maturity IV. Monday and Tuesday are considered as begin-week, Wednesday is mid-week, and Thursday is the end-week.

Table 5 discusses the performance of IV_CHF, IV_EUR and IV_GBP to estimate the value of CHF, EUR and GBP options, respectively, for the one-week horizon. The MSE measure indicated that one-month (with call pricing error = 0.040 and put pricing error = 0.018), two-month (with call pricing error = 0.070 and put pricing error = 0.030) and three-month (with call pricing error = 0.065 and put pricing error = 0.025) maturity IV_CHF on Monday held appropriate information to estimate the CHF call and put options. Identically, the one-month (with call pricing error = 0.060 and put pricing error = 0.010), two-month (with call pricing error = 0.070 and put pricing error = 0.015) and three-month (with call pricing error = 0.070 and put pricing error = 0.020) maturity IV_EUR on Monday was superior for pricing the EUR call options and put options. Finally, the Monday one-month (with call pricing error = 0.065 and put pricing error = 0.018), two-month (with call pricing error = 0.070 and put pricing error = 0.025) and three-month (with call pricing error = 0.080 and put pricing error = 0.030) maturity IV_GBP contained useful information in estimating the GBP call options price and GBP put options price. In summary, on Monday (beginning weekday), the one-month maturity IV_CHF (with call pricing error = 0.040 and put pricing error = 0.018), IV_EUR (with call pricing error = 0.060 and put pricing error = 0.010) and IV_GBP (with call pricing error = 0.065 and put pricing error = 0.018) held appropriate information in estimating the CHF, EUR and GBP options price.

Table 5. Estimate options pricing error for the one-week horizon.

One-Week Estimate Horizon	Options	IV_CHF			IV_EUR			IV_GBP		
		1-Month Maturity	2-Month Maturity	3-Month Maturity	1-Month Maturity	2-Month Maturity	3-Month Maturity	1-Month Maturity	2-Month Maturity	3-Month Maturity
Panel A: Pricing error under MAE measure										
Mon to Mon	CALL	0.130 [2]	0.170 [2]	0.170 [2]	0.180 [2]	0.185 [2]	0.183 [2]	0.200 [2]	0.202 [2]	0.225 [2]
	PUT	0.080 [2]	0.098 [2]	0.110 [2]	0.075 [2]	0.085 [2]	0.100 [2]	0.009 [2]	0.105 [2]	0.115 [2]
Tue to Tue	CALL	0.175	0.220	0.215	0.200	0.198	0.200	0.260	0.275	0.275
	PUT	0.010	0.110	0.130	0.110	0.115	0.115	0.125	0.135	0.130
Wed to Wed	CALL	0.210	0.230	0.235	0.200	0.228	0.200	0.228	0.270	0.275
	PUT	0.010	0.105	0.135	0.104	0.120	0.130	0.115	0.130	0.131
Thu to Thu	CALL	0.195	0.225	0.210	0.182	0.220	0.215	0.210	0.255	0.229
	PUT	0.098	0.118	0.130	0.080	0.100	0.125	0.110	0.115	0.120
Fri to Fri	CALL	0.160	0.170	0.180	0.230	0.340	0.240	0.225	0.280	0.240
	PUT	0.090	0.010	0.130	0.145	0.145	0.150	0.115	0.125	0.160
Panel B: Pricing error under MSE measure										
Mon to Mon	CALL	0.040 [3,*]	0.070 [3]	0.065 [3]	0.060 [3,*]	0.070 [3]	0.070 [3]	0.065 [3,*]	0.070 [3]	0.080 [3]
	PUT	0.018 [3,*]	0.030 [3]	0.025 [3]	0.010 [3,*]	0.015 [3]	0.020 [3]	0.018 [3,*]	0.025 [3]	0.030 [3]
Tue to Tue	CALL	0.095	0.170	0.150	0.080	0.125	0.085	0.085	0.100	0.115
	PUT	0.035	0.050	0.055	0.020	0.025	0.030	0.040	0.040	0.040
Wed to Wed	CALL	0.115	0.120	0.125	0.085	0.100	0.135	0.120	0.170	0.140
	PUT	0.030	0.050	0.060	0.030	0.045	0.035	0.050	0.055	0.050
Thu to Thu	CALL	0.080	0.200	0.100	0.075	0.095	0.095	0.090	0.115	0.105
	PUT	0.050	0.070	0.050	0.015	0.020	0.030	0.020	0.040	0.040
Fri to Fri	CALL	0.055	0.100	0.070	0.075	0.205	0.195	0.165	0.179	0.180
	PUT	0.020	0.045	0.070	0.040	0.065	0.060	0.025	0.026	0.038
Panel C: Pricing error under MAPE measure										
Mon to Mon	CALL	0.140 [1]	0.182 [1]	0.190 [1]	0.201 [1]	0.206 [1]	0.210 [1]	0.210 [1]	0.212 [1]	0.230 [1]
	PUT	0.092 [1]	0.115 [1]	0.116 [1]	0.080 [1]	0.090 [1]	0.105 [1]	0.105 [1]	0.115 [1]	0.120 [1]
Tue to Tue	CALL	0.190	0.230	0.235	0.210	0.211	0.215	0.261	0.280	0.285
	PUT	0.101	0.120	0.135	0.120	0.125	0.132	0.130	0.135	0.138
Wed to Wed	CALL	0.215	0.241	0.242	0.210	0.230	0.241	0.242	0.280	0.282
	PUT	0.115	0.122	0.126	0.114	0.126	0.132	0.125	0.130	0.136
Thu to Thu	CALL	0.225	0.235	0.235	0.205	0.225	0.227	0.220	0.260	0.261
	PUT	0.120	0.125	0.127	0.101	0.120	0.124	0.125	0.125	0.127
Fri to Fri	CALL	0.170	0.200	0.205	0.240	0.250	0.275	0.235	0.283	0.284
	PUT	0.105	0.120	0.125	0.160	0.149	0.165	0.124	0.130	0.36

Note: The implied volatility of Swiss franc (CHF), Euro (EUR) and British pound (GBP) options are represented by IV_CHF, IV_EUR, and IV_GBP, respectively. The closing period IV_CHF, IV_EUR, and IV_GBP is computed using one-month (options trading days between 2 and 30), two-month (options trading days between 31 and 60), and three-month (options trading days between 61 and 90) maturity CHF, EUR, and GBP options are used to estimate call and put price by Equations (11) and (12), respectively. The MAE, MSE, and MAPE methods are employed by Equation (13), Equation (14), and Equation (15), respectively, to measure the closing OPE. The OPE under MAE, MSE and MAPE measures are given in panels A, B, and C, respectively, for one-week estimate horizon (that is, IV of Monday, Tuesday, Wednesday, Thursday, and Friday to forecast option price of Monday, Tuesday, Wednesday, Thursday, and Friday of the next week). The higher, mid, and lower pricing errors are denoted by superscripts [1, 2], and [3], respectively, among MAE, MSE, and MAPE measures for each option for one month, two-month and three-month maturity. The smallest pricing error is represented by * for one-month, two-month, and three-month maturity IV. Monday and Tuesday are considered as begin-week, Wednesday is mid-week, and Thursday is the end-week.

Table 6 analyses the performance of IV_CHF, IV_EUR and IV_GBP for the one-month horizon, to estimate the price of the CHF, EUR and GBP options, respectively. The MSE measure showed that the one-month (with call pricing error = 0.055 and put pricing error = 0.045), two-month (with call pricing error = 0.050 and put pricing error = 0.030), and three-month (with call pricing error = 0.085 and put pricing error = 0.040) maturity IV_CHF on Tuesday provides vital information in computing the CHF call options price, and CHF put options. The similar result was reported for EUR when the one-month (with call pricing error = 0.095 and put pricing error = 0.030), two-month (with call pricing error = 0.070 and put pricing error = 0.020), and three-month (with call pricing error = 0.080 and put pricing error = 0.040) maturity IV_EUR of Tuesday also outperformed for pricing EUR call options price, and EUR put options price. Finally, the Tuesday one month (with call pricing error = 0.080 and put pricing error = 0.046), two-month (with call pricing error = 0.075 and put pricing error = 0.045), and three-month (with call pricing error = 0.105 and put pricing error = 0.050) maturity IV_GBP contained appropriate information is estimating the GBP call options price and GBP put options price. In summary, on Tuesday, two-month maturity (beginning weekday) IV_CHF (with call pricing error = 0.050 and put pricing error = 0.030), IV_EUR (with call pricing error = 0.070 and put pricing error = 0.020) and IV_GBP (with call pricing error = 0.075 and put pricing error = 0.045) held useful information in calculating the CHF options price, EUR options price and GBP options price.

Table 6. Estimate options pricing error for the one-month horizon.

One-Month Estimate Horizon	Options	IV_CHF 1-Month Maturity	IV_CHF 2-Month Maturity	IV_CHF 3-Month Maturity	IV_EUR 1-Month Maturity	IV_EUR 2-Month Maturity	IV_EUR 3-Month Maturity	IV_GBP 1-Month Maturity	IV_GBP 2-Month Maturity	IV_GBP 3-Month Maturity
Panel A: Pricing error under MAE measure										
Mon to Mon	CALL	0.225	0.215	0.220	0.245	0.220	0.225	0.240	0.230	0.240
	PUT	0.160	0.150	0.155	0.220	0.115	0.135	0.130	0.120	0.150
Tue to Tue	CALL	0.165 [2]	0.160 [2]	0.190 [2]	0.210 [2]	0.195 [2]	0.210 [2]	0.195 [2]	0.120 [2]	0.235 [2]
	PUT	0.145 [2]	0.140 [2]	0.145 [2]	0.110 [2]	0.095 [2]	0.125 [2]	0.129 [2]	0.115 [2]	0.140 [2]
Wed to Wed	CALL	0.215	0.220	0.220	0.235	0.225	0.225	0.260	0.250	0.270
	PUT	0.150	0.145	0.235	0.145	0.135	0.150	0.165	0.150	0.150
Thu to Thu	CALL	0.215	0.225	0.220	0.225	0.210	0.230	0.270	0.250	0.255
	PUT	0.150	0.145	0.170	0.120	0.110	0.140	0.130	0.120	0.145
Fri to Fri	CALL	0.220	0.210	0.210	0.215	0.200	0.220	0.255	0.245	0.250
	PUT	0.150	0.150	0.160	0.115	0.105	0.130	0.135	0.120	0.150
Panel B: Pricing error under MSE measure										
Mon to Mon	CALL	0.105	0.100	0.140	0.100	0.090	0.090	0.140	0.120	0.120
	PUT	0.090	0.050	0.115	0.045	0.030	0.045	0.050	0.055	0.060
Tue to Tue	CALL	0.055 [3]	0.050 [3,*]	0.085 [3]	0.095 [3]	0.070 [3,*]	0.080 [3]	0.080 [3]	0.075 [3,*]	0.105 [3]
	PUT	0.045 [3]	0.030 [3,*]	0.040 [3]	0.030 [3]	0.020 [3,*]	0.040 [3]	0.046 [3]	0.045 [3,*]	0.050 [3]
Wed to Wed	CALL	0.105	0.098	0.125	0.120	0.110	0.130	0.160	0.150	0.155
	PUT	0.060	0.040	0.050	0.050	0.040	0. 050	0.105	0.095	0.100
Thu to Thu	CALL	0.100	0.090	0.100	0.115	0.090	0.100	0.160	0.125	0.150
	PUT	0.096	0.065	0.070	0.055	0.035	0.045	0.055	0.050	0.070
Fri to Fri	CALL	0.125	0.100	0.105	0.105	0.100	0.090	0.135	0.130	0.130

	PUT	0.090	0.070	0.080	0.040	0.030	0.050	0.050	0.050	0.070
Panel C: Pricing error under MAPE measure										
Mon to Mon	CALL	0.230	0.230	0.235	0.250	0.230	0.235	0.245	0.240	0.245
	PUT	0.165	0.155	0.158	0.225	0.120	0.140	0.135	0.126	0.140
Tue to Tue	CALL	0.170 [1]	0.175 [1]	0.200 [1]	0.215 [1]	0.200 [1]	0.215 [1]	0.200 [1]	0.130 [1]	0.240 [1]
	PUT	0.154 [1]	0.150 [1]	0.152 [1]	0.116 [1]	0.110 [1]	0.130 [1]	0.130 [1]	0.120 [1]	0.146[1]
Wed to Wed	CALL	0.220	0.224	0.225	0.240	0.230	0.230	0.255	0.250	0.260
	PUT	0.155	0.150	0.175	0.150	0.140	0.155	0.170	0.155	0.160
Thu to Thu	CALL	0.221	0.225	0.222	0.230	0.225	0.228	0.275	0.245	0.252
	PUT	0.162	0.158	0.175	0.130	0.125	0.142	0.135	0.131	0.134
Fri to Fri	CALL	0.230	0.220	0.221	0.220	0.210	0.235	0.260	0.250	0.256
	PUT	0.120	0.125	0.130	0.120	0.112	0.135	0.140	0.125	0.153

Note: The implied volatility of Swiss franc (CHF), Euro (EUR) and British pound (GBP) options are represented by IV_CHF, IV_EUR, and IV_GBP, respectively. The closing period IV_CHF, IV_EUR, and IV_GBP is computed using one-month (options trading days between 2 and 30), two-month (options trading days between 31 and 60), and three-month (options trading days between 61 and 90) maturity CHF, EUR, and GBP options are used to estimate call and put price by Equations (11) and (12), respectively. The MAE, MSE, and MAPE methods are employed by Equation (13), Equation (14), and Equation (15), respectively, to measure the closing OPE. The OPE under MAE, MSE and MAPE measures are given in panels A, B, and C, respectively, for one-week estimate horizon (that is, IV of Monday, Tuesday, Wednesday, Thursday, and Friday to forecast option price of Monday, Tuesday, Wednesday, Thursday, and Friday of the next month). The higher, mid, and lower pricing errors are denoted by superscripts [1, 2], and [3], respectively, among MAE, MSE, and MAPE measures for each option for one month, two-month and three-month maturity. The smallest pricing error is represented by * for one-month, two-month, and three-month maturity IV. Monday and Tuesday are considered as begin-week, Wednesday is mid-week, and Thursday is the end-week.

5. Conclusions

Regarding the IV forecast of FX volatility, the within-week horizon provides a mixed scenario. It appears that the IV does not hold the relevant information to forecast the volatility of the underlying currency of options over a one- to four-day predictive period. Therefore, the IV is considered ineffective for estimating the price of currency options for the within-a-week horizon. The one-month and two-month options maturity, begin-week day, and closing period IV content appropriate and useful information to forecast RV for the one-week and one-month forecast horizon, respectively. It suggests the significance of information content embedded in one-month and two-month maturity IV in predicting the volatility of the underlying currency of options for the one-week and one-month forecast horizon, respectively. Therefore, a one-month and two-month maturity IV is appropriate for computing the currency options price for the one-week and one-month estimated horizon, respectively.

In summary, three-month options maturity IV does not contain critical information about the future volatility of underlying currency and pricing currency options for less than a one-month forecast horizon. Further, intraday IV incorporating all information is not relevant or appropriate in computing currency options price for less than a week options price estimated horizon. It may conclude that the cluster characteristics of FX volatility when both information obtaining day (e.g., Monday) and predicting day (i.e., Friday) lie in the same cluster (Le et al. 2021). The IV based on the closing price and the beginning of a week subsumes most of the appropriate information compared to opening and midday periods of a trading day and other days of the week in forecasting the volatility of foreign exchange and computing currency options price. It can be described by the inequality of relevant information obtained between weekdays or the steady reduction in vital information from the middle of the week. Our finding differs from the research result of Wang and Wang (2016) that found that volatility index of S&P 500 around noon contained the most relevant information to predict RV. Moreover, The IV based on the options with shorter maturity is suitable for pricing currency options for a shorter horizon. Similarly, the IV for longer maturity options contains vital information for pricing currency options for a longer horizon. The similar findings were found in the research of Le et al. (2021) for the AUD option. The study sample was gathered from 2010 to 2020 and captured the post-crisis economic circumstance. Further, to diminish the sample-specific limitation, future research could analyse the performance of intraday IV for the different samples or situations, including both pre-crisis and during crisis periods.

The survey results provide several insights for market practitioners to consider when constructing the organisational trading and risk management framework. Foreign currency options have been using broadly to protect the businesses, especially multinational corporations from the exchange rate risks. However, the inaccuracy of currency options prices may lead to the massive hedging costs. The development of new technology allows trading organisations to extract a rich and more reliable information from market to forecast the currency options price, thus improving the accuracy and efficiency of hedging activities in businesses. This paper provides valuable information for the market practitioners to develop the hedging strategies.

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