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Currency Option Prices Good Predictors  
of Future Exchange Rate Volatility?**

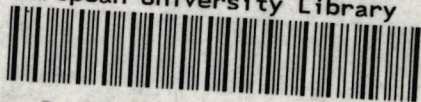
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**ECONOMICS DEPARTMENT**

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# Are Standard Deviations Implied in Currency Option Prices Good Predictors of Future Exchange Rate Volatility ?

Mariusz TAMBORSKI \*

February 1994

## Abstract

In this paper, we use the currency option pricing model with stochastic interest rates and transactions costs developed by Tamborski (1994) to investigate the strong rationality of the market in its *ex ante* prediction of the one-month-ahead exchange rate volatility for six currencies using the data from PHLX. We find that in OLS estimations, the strong rationality is rejected only for the German mark and the Swiss franc. For four other currencies: the Australian dollar, the British pound, the Canadian dollar and the Japanese yen we find that the standard deviation implied in currency options prices is valuable predictor of future currency return variance.

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# 1 Introduction

Standard deviations implied in stock option prices are often employed as predictors of future stock return volatility. Latane and Rendleman (1976) derive standard deviations implied in call option prices on the assumption that investors price stock options according to the Black and Scholes model. Although there is a basic inconsistency in using this model to obtain predictions of the presumably non-stationary variance [Christie (1982)], results reported by Latane and Rendleman indicate that the approach is valuable, at least from a pragmatic point of view. They find that the weighted average implied standard deviation is highly correlated with actual standard deviation.

MacBeth and Merville (1979) use an implied variance rate for at-the-money options. Beckers (1981) extends the previous work for the effects of bid-ask spreads on implied measures, alternative weighting techniques, and non-simultaneity in closing stock and option prices, and also finds implied standard deviations highly correlated with actual standard deviations.

The study presented by Scott and Tucker (1989) extends the methodologies of Latane and Rendleman and Beckers to foreign exchange options in order to assess the predictive power of standard deviations implied in currency call option prices. They use the transactions data from the Philadelphia Stock Exchange for the period of March 1983 through to March 1987 and, despite documented variance non-stationarity, they find a strong predictive relationship between actual volatilities and implied volatilities. Moreover, they show that forecasts implied using a Black and Scholes type stationary parameter currency model are as accurate as forecasts implied using a more complex constant elasticity of variance (CEV) currency model.

However, some studies do not present implied volatility as a good predictor of future volatility of underlying assets. De la Bruslerie (1988) finds, in the case of options on interest rates<sup>1</sup>, that the correlation between implied and actual volatilities in absolute terms (levels) is rather modest (0.6) and it is low (0.2) for changes of volatilities.

Frankel and Wei (1991) investigate the rationality of the market in forming its *ex ante* anticipation of the one-month-ahead exchange rate volatility for four currencies using the data from PHLX. The mar-

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<sup>1</sup> US Treasury bonds.



ket *ex ante* anticipation of exchange volatility is inferred from American call option contracts on foreign currencies. They reject the strong rationality.<sup>2</sup> This is true both in ordinary least squares (OLS) and in seemingly unrelated regression (SUR) estimations, with or without correction for overlapping observations. However, using a Henriksson and Merton nonparametric test, Frankel and Wei prove that the market anticipation satisfies the weaker rationality condition.<sup>3</sup>

One of the central findings of their paper is that implicit volatilities extracted from options prices using the Garman and Kohlhagen assumptions are not optimal forecasts of future volatilities. The rejection of strong rationality can be due to investors' mistakes in estimating the future volatility but it can also be due to the fact that Weil and Frankel use Garman and Kohlhagen formula to evaluate American options. Another further reason may be the failure of one of the Garman and Kohlhagen assumptions. If the market participants take this into account in forming their anticipations, the anticipated volatility inferred by the Garman and Kohlhagen formula may be incorrect as an estimate of investors' forecasts.<sup>4</sup> In our paper, we use the Tamborski (1994) model of option pricing with stochastic interest rates and transaction costs to investigate whether this model allows for a better investors' forecast of the future volatility.

The paper is organized as follows. The second section presents the European currency option model with stochastic interest rates and transaction costs. The third section contains a description of the data. An estimation of the variance-covariance matrix of exchange and interest rates is given in the fourth section. In the fifth section, we examine the ability of standard deviations implied in call currency options to predict a future volatility of exchange rates. Conclusions are drawn in the last section.

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<sup>2</sup> A strong rationality means that the implied standard deviation is an unbiased predictor of the future realized standard deviation.

<sup>3</sup> A weaker version of rationality means that the market can rationally forecast the direction of change, regardless of the magnitude of the change.

<sup>4</sup> For Frankel and Wei one explanation of the bias can be the fact that, contrary to the assumption underlying the Black-Scholes and Garman-Kohlhagen formulas, the spot exchange rate process contains significant jumps.

## 2 European foreign currency option pricing model with stochastic interest rates and transaction costs

Building on the classic model of Black and Scholes (1973) regarding European options on stock, any model of foreign currency options must incorporate foreign as well as domestic interest rates. This issue arises from the fact that default risk-free foreign bonds, as well as domestic bonds, represent a risk-free alternative to a hedge portfolio of spots and options on foreign exchange.

Garman and Kohlhagen (1983) derived the first currency option pricing model:<sup>5</sup>

$$c = e^{-r^*T} SN(d_1) - e^{-rT} XN(d_2) \quad (1)$$

where

$$d_1 = \frac{\ln(\frac{S}{X}) + (r - r^* + \frac{1}{2}\sigma_s^2)T}{\sigma_s\sqrt{T}},$$

$$d_2 = d_1 - \sigma_s\sqrt{T},$$

$N(d) = \int_{-\infty}^d \frac{1}{\sqrt{2\pi}} \exp(\frac{-x^2}{2}) dx$  (the cumulative standard normal distribution),  $c$  is the price of the European call option,  $S$  is the spot exchange rate,  $X$  is the strike price,  $r$  is the instantaneous domestic short rate of interest,  $r^*$  is the instantaneous foreign short rate of interest,  $T$  is the time until expiration, and  $\sigma_s$  represents the instantaneous standard deviation of  $S$ . The Garman and Kohlhagen model assumes that there are no transaction costs and the interest rates are known and constant through time.

However, in the presence of nonzero transaction costs, the arbitrage argument used by Garman and Kohlhagen to price options can no longer be used: since replicating the option by a dynamic strategy would be infinitely costly, no effective option price bounds are implied. Leland (1985) shows that there is an alternative replicating strategy to the Black and Scholes model for stocks, in which transaction costs remain bounded even as the revision period becomes short. Leland's strategy replicates the option return inclusive of transaction cost, with an error which is uncorrelated with the market and approaches zero as the revision period becomes small. Moreover, the transaction costs put bounds on option prices. Leland's alternative strategy depends upon

<sup>5</sup>Biger and Hull (1983), Giddy (1983) and Grabbe (1983) develop very similar models.



the level of transaction costs and upon the revision interval (exogenously given). These additional parameters, are introduced in a very simple way, through an adjustment of the volatility in the Black and Scholes formula.

Merton (1992) examines the effects of transactions costs on derivative security pricing by using the two-period version of the Cox-Ross-Rubinstein binomial option pricing model when there are proportional transaction costs on the underlying asset. In a discrete-time framework, he constructs a portfolio of the risky asset and riskless bonds that precisely replicates the option value at maturity of the option with transaction costs.

Boyle and Vorst (1992) extend Merton's analysis to several periods. Their method proceeds by constructing the appropriate replicating portfolio with transaction costs at each trading interval. They derive also a simple Black and Scholes type approximation for the option prices with transaction costs. Transaction costs enter in the formula through the adjustment of the variance. This approach is similar to the Leland's, but the variance adjustment in the Boyle and Vorst model is larger than that derived by Leland.

The replicating strategies for option pricing proposed by Leland, Merton, and Boyle and Vorst imply finite transaction costs and still generate, with probability one, a payoff equal to that of the option. However, the strategies considered in these models are not chosen to satisfy some optimality criteria that investors may wish to meet.

The optimality criterion for investors can be defined in at least two different ways. One definition is in terms of expected utility. In this approach, the chosen strategy should maximize the expected value of a constant relative risk-averse utility function, for a *given level of wealth*. Constantinides (1986) proposes an approximate solution to the portfolio choice problem in the presence of proportional transaction costs. The investor maximizes the expected value of his infinite-horizon utility function. Portfolio strategies (a proportion of the risky and risk-free assets in the portfolio) are computed numerically under the assumption that the investor in each period consumes a fixed proportion of his wealth. Dumas and Luciano (1991) assume that the investor does not consume wealth along the way, but consumes everything at the terminal point in time. His objective is to maximize the expected utility derived from that terminal consumption. In contrast to Constantinides, their formulation of the portfolio strategy under proportional transac-



tion costs leads to an exact solution. The exact solution is in the form of two control barriers. These set - for given level of transaction costs, investor's risk aversion, excess return on the risky asset, and variance of return on risky asset - the upper and lower limits (a proportion of risky and riskless assets) of imbalance in the portfolio, which will be tolerated before any action is taken. This implies that the frequency of portfolio revision is generally stochastic.

Another criterion is to minimize the initial cost of obtaining a *given terminal payoff* that is at least as large as that from the option being hedged. The advantage of the minimum cost criteria is that the optimal strategies are independent of an investor's preferences. Bensaid, Lesne, Pages and Scheinkman (1992) construct a dynamic programming algorithm to obtain the cost-minimizing trading strategy. However, in their algorithm, they introduce the entire path of the stock price process as a state variable. Thus, when the number of trading dates is large, the implementation of their algorithm for a general payoff is likely to be difficult. Edirisinghe, Naik and Uppal (1993) developed a two-stage dynamic programming model to account for fixed and variable trading costs, lot size constraints, and position limits on trading. Their least-cost replication strategy for hedging the payoff (convex or nonconvex) of contingent claims introduces the current stock and bond position of the investor as state variables. They show that in the presence of trading frictions, it is no longer optimal to revise one's portfolio in each period. Moreover, it is optimal to establish a larger position initially, and to reduce the amount of trading in later periods.

In spite of a strong conviction that options should be priced in an optimal portfolio-investment framework, these models give no straightforward and analytical solution to the option pricing problem. The Leland-style transaction costs approach, which assumes the fixed interval between portfolio rebalancing (in general non optimal), has an advantage in providing an analytical solution.

Another assumption made by Garman and Kohlhagen in deriving their option pricing model, the constancy of interest rates, has become a matter of major concern to both academic and investment communities. Many studies, like Adams and Wyatt (1987), Choi and Hauser (1990), report pricing biases in European and American call options when interest rate uncertainty is not acknowledged in the model. For currency options, the problem is more complicated because (a) there are not one but two - domestic and foreign - interest rates to worry

about, and (b) the international interest rate differential may dictate the rationality and timing of exercising options.

The European currency option model with stochastic discount bonds was derived in 1983 by Grabbe. It is based on Merton's stock option pricing model including proportional dividend. However, neither the Merton or Grabbe models explicitly assume stochastic processes for domestic and foreign interest rates. To do this, use must be made of a model of bond prices. Models of this nature have been investigated by Hsieh (1988), Rabinovitch (1989) and Hilliard, Madura, and Tucker (1991). They apply Vasicek's (1977) bond pricing model to both foreign and domestic bonds.

Tamborski (1994) addresses both problems and develops a currency option pricing model under stochastic interest rates and transaction costs. He assumes that the interest parity holds, and domestic and foreign bond prices have local variances that depend only on time. Tamborski applies Leland's technique for replicating option returns in the presence of transaction costs to the Garman and Kohlhagen formula modified to include the assumptions of Vasicek bond pricing model. The stochastic interest rates and transaction costs are introduced in a simple way, through an adjustment of the volatility in the Garman and Kohlhagen currency option pricing model. Hedging errors of the modified replicating strategies inclusive of stochastic interest rates and transaction costs are uncorrelated with the market and approach zero with more frequent revision. Therefore, the Tamborski currency option pricing model puts upper and lower bounds on option prices. The symmetry of the bid and ask prices of the currency around its zero-transaction-cost price does not imply a corresponding symmetry for the bid and ask prices of the call option.

On one hand the equation (2) sets an upper bound on the option price,  $\hat{c}_{\max}$ , since if the price exceed that amount the option could be constructed by the replicating strategy.

$$\hat{c}(S, X, \lambda_{\max}, r, r^*, T) = e^{-r^*T} SN(\hat{d}_1) - e^{-rT} XN(\hat{d}_2) \quad (2)$$

where

$$\hat{d}_1 = \frac{\ln(\frac{S}{X}) + (r - r^* + \frac{1}{2}\lambda_{\max}^2)T}{\lambda_{\max}\sqrt{T}},$$

$$\hat{d}_2 = \hat{d}_1 - \lambda_{\max}\sqrt{T},$$

$$\lambda_{\max}^2 = \hat{\sigma}^2[1 + k + \frac{k\sqrt{2/\pi}}{(\hat{\sigma}\sqrt{\Delta t})}],$$

$$\hat{\sigma}^2 = \sigma_s^2 + \frac{T^2}{3}(\sigma_r^2 + \sigma_{r^*}^2 - 2\sigma_{rr^*}) + T(\sigma_{sr^*} - \sigma_{sr}),$$



$k$  is the round trip transaction cost, measured as a fraction of the volume of transaction in underlying asset,  $\Delta t$  is the revision period (frequency of revision),  $\sigma$ -terms ( $\sigma_s$ ,  $\sigma_r$ , and  $\sigma_{r^*}$ ) represent instantaneous standard deviations,  $\sigma_{rr^*} = \rho_{rr^*}\sigma_r\sigma_{r^*}$ ,  $\sigma_{sr^*} = \rho_{sr^*}\sigma_s\sigma_{r^*}$  and  $\sigma_{sr} = \rho_{sr}\sigma_s\sigma_r$  are covariances.

On the other hand, the option price can be never less than  $\hat{c}_{\min}$ , where  $\hat{c}_{\min}$  is given by the equation (3) with the volatility  $\lambda_{\min}$ :

$$\hat{c}(S, X, \lambda_{\min}, r, r^*, T) = e^{-r^*T}SN(\hat{d}_1) - e^{-rT}XN(\hat{d}_2) \quad (3)$$

where

$$\begin{aligned} \hat{d}_1 &= \frac{\ln(\frac{S}{X}) + (r - r^* + \frac{1}{2}\lambda_{\min}^2)T}{\lambda_{\min}\sqrt{T}}, \\ \hat{d}_2 &= \hat{d}_1 - \lambda_{\min}\sqrt{T}, \\ \lambda_{\min}^2 &= \hat{\sigma}^2 \left[ 1 - k - \frac{k\sqrt{2/\pi}}{(\hat{\sigma}\sqrt{\Delta t})} \right] \text{ when } \hat{\sigma} > \frac{k}{(1-k)}\sqrt{\frac{2}{\pi\Delta T}} \text{ and} \\ \lambda_{\min}^2 &= 0 \text{ when } \hat{\sigma} < \frac{k}{(1-k)}\sqrt{\frac{2}{\pi\Delta T}}, \\ \hat{\sigma}^2 &= \sigma_s^2 + \frac{T^2}{3}(\sigma_r^2 + \sigma_{r^*}^2 - 2\sigma_{rr^*}) + T(\sigma_{sr^*} - \sigma_{sr}). \end{aligned}$$

The "pure" Garman and Kohlhagen formula holds in the limiting case of constant interest rates and zero transactions costs. In this case  $\sigma_s = \lambda_{\max} = \lambda_{\min}$  and  $c = \hat{c}_{\max} = \hat{c}_{\min}$ . If the price of an option exceeds  $\hat{c}_{\max}$ , we could make profits higher than the risk-free rate, by selling the option and buying the duplicating portfolio containing  $\frac{\partial \hat{c}_{\max}}{\partial F}$  long futures contracts and selling  $\frac{\partial \hat{c}_{\max}}{\partial F}F - \hat{c}_{\max}$  bonds (borrowing).<sup>6</sup> If the price of an call option is less than  $\hat{c}_{\min}$ , an investor could buy this "underpriced" option, "undo" it by following the offsetting replicating strategy, and make a return after transaction costs which exceeded the risk-free rate.<sup>7</sup>

Between these two transaction cost adjusted option prices,  $\hat{c}_{\min}$  and  $\hat{c}_{\max}$ , will exist a no man's land in which option prices are too low for an investment hedge<sup>8</sup> to compete with a risk-free interest rate

<sup>6</sup>Tamborski assumes that the interest parity holds  $F(t, T) = S(t) \frac{e^{-r^*(T-t)}}{e^{-r(T-t)}}$  and that forward and futures prices are the same.

<sup>7</sup> Initially, the investor buys the call option, sells  $\frac{\partial \hat{c}_{\min}}{\partial F}$  futures contracts and buys  $\frac{\partial \hat{c}_{\min}}{\partial F}F - \hat{c}_{\min}$  bonds (investing or lending). Then he follows the replicating strategy by maintaining the neutral position ratio (the number of futures contracts held for each call) until the maturity date of the option. Finally, he closes out his position by selling the option, buying the futures contract and selling the bonds (borrowing).

<sup>8</sup> An investment hedge consists of a long position in futures contract and a short position in call options. This hedge will require a positive net investment which will earn the risk-free rate. If the hedge consists of a short position in futures and a long



and too high for a borrowing hedge to compete with other forms of borrowing. In other terms, for option prices within this range, neither hedges duplicating a *long call option* nor hedges duplicating a *short call option* are particularly attractive.

### 3 Description of the data

In this paper we employ transactions data for European currency call options traded on the Philadelphia Stock Exchange (PHLX). The data base compiled by the PHLX and Ohio State University contains the following information for each option trade: date of trade, currency, maturity date, strike price, number of contracts, number of trades, opening (high, low and closing) option price, time of opening (high, low and closing) trade, and foreign currency spot price at opening (high, low and closing) trade available from the Telerate data service.

American and European<sup>9</sup> calls and puts on eight currencies<sup>10</sup> are traded in one, two, three, six, nine and twelve month cycles, the expiration months being March, June, September and December in addition to the two nearest-term months. Contracts expire on the Saturday before the third Wednesday of the month, with settlement taking place on this third Wednesday. At any given time, only the three shortest term contracts are traded. When a new cycle is opened, contracts are offered with strike prices forming a band around the current spot exchange rate, i.e., near, in and out of the money. If exchange rates move such that existing contracts may become completely in or out of the money, a new contract will be opened mid-cycle, again completing the band around the current spot price. Options contracts are, therefore, available at any time which are at, in and out of the money.

In our study we test European call options on six currencies: the British pound, the Japanese yen, the German mark, the Canadian dollar, the Swiss franc and the Australian dollar. Our option data base position in call options, the hedge supplies funds which will cost the risk-free rate and it is called a *borrowing hedge*.

<sup>9</sup>European options account for less than 10 % of the total number of trades.

<sup>10</sup>The PHLX began trading on 10 December 1982 with the British pound. By mid-February 1983, option contracts on the Japanese yen, the German mark, the Canadian dollar and the Swiss franc were being traded. Options on the French franc were added in September 1984. Contracts on the European Currency Unit (ECU) and the Australian dollar began in 1986 and 1987, respectively.

begins in December 1987 and extends through to September 1991.<sup>11</sup> We use closing option prices. The initial data consists of a total of 3901 observations which correspond to 6779 trades and 431191 call contracts. However, the sample used here is smaller than this because of a few deletions based on the following four criteria. First, to avoid problems associated with the near maturity options, we eliminate all option series that have less than 7 days before their expiration date. Second, we delete all observations for options with a price of less than ten cents. These observations are eliminated because hedging strategies using these options would be unrealistic since they would require investment in a large number of contracts. Third, we eliminate all options which are deep-out-of-the-money or deep-in-the-money. Finally, we eliminate all data records that appear to be in error.<sup>12</sup> The results of this deletion procedure are presented in more detail in table 1. Our final sample consists of 2797 call observations with 4839 trades and 329593 call contracts. A breakdown of the sample by currency is contained in table 2.

The foreign and domestic interest rates ( $r^*$  and  $r$  respectively) employed in the tests reported in the next sections are based on Eurocurrency interest rates obtained from the Datastream data base. Eurocurrency interest rates are available in maturities of seven days, and one, three, six and 12 months. We use the Eurocurrency seven days interest rates for the US, Great Britain, Canada, Germany and Japan. The interbank call is used as Australian interest rate.

Finally, when testing the model with transaction costs, a market participant executing trades must be chosen to identify the relevant transaction costs. The PHLX Foreign Currency Options Market is based on a specialist trading system.

<sup>11</sup> In the original database obtained from the PHLX, there was some missing data, especially between July 13, 1989 and September 12, 1989. In total, there were missing 22 days of data in 1988, 50 days in 1989, 8 days in 1990 and 3 days in 1991. For these periods we use the closing option prices published daily in *The Wall Street Journal*. However, it should be kept in mind that the use of closing prices from *The Wall Street Journal* have some problems since they are not necessarily transaction prices, they do not always reflect a synchronization between the option price and the price of the underlying foreign currency, and they do not give any indication of the depth of the market at that price.

<sup>12</sup> Options excluded using this criterion are ones that have obvious data errors. Examples of transactions eliminated are: a) the same Australian call observation appears twice in two different places (files) of the data base; b) a call on the Japanese yen expiring in November 1990 was traded four days after the expiration settlement date.



Table 1  
Description of deleted data. European call options

Underlying currency	$t < 7$ days			call price $< 0.1\$$			$S - 10 > X > S + 10^a$			Data error		
	obse rvat ions	trad es	contr acts	obse rvat ions	trad es	contr acts	obse rvat ions	trad es	contr acts	obse rvat ions	trad es	contr acts
Australian dollar	35	47	4092	27	41	3658	16	20	3055	108	164	24360
British pound	48	89	3619	8	10	468	17	27	2894	103	180	7690
Canadian dollar	118	274	8798	38	67	4876	1	5	214	299	539	19461
German mark	43	61	2863	15	28	709	32	41	1425	27	41	747
Japanese yen	39	71	1549	23	49	3733	7	8	59	20	41	668
Swiss franc	26	47	1301	30	58	4232	13	17	312	11	157	815
TOTAL	309	589	22222	141	253	17676	86	118	7959	568	980	53741

<sup>a</sup>For British pound  $S - 15 > X > S + 15$ .  $S$  is the spot exchange rate in cents per unit of foreign currency and  $X$  is the strike price.

In addition, market makers are assigned to each currency to support the specialist by taking up to fifty percent of all trades in certain markets. Unlike the specialist, the market maker does not have to conduct a market in the assigned currency option. Because of this, the market maker should be the low marginal cost trader. We have, therefore, chosen the market maker as the relevant market participant. The market maker's transaction costs are estimated to be:<sup>13</sup>

Transaction costs per contract

OCC initial fee	\$ 0.05
PHLX broker fee	\$ 2.00
PHLX exchange fee	\$ 0.05
PHLX proportional value charge	0.12%
Exercise cost per line item	
OCC exercise fee per line item	\$ 35.00
Cost of foreign exchange trade	\$ 50.00

These transaction costs include fixed transaction costs as well as variable costs. However for theoretical reasons we only use in this study the round trip transaction cost, measured as a fraction of the volume of transaction. This transaction cost,  $k$  is estimated to be equal to 0.2%.<sup>14</sup>

<sup>13</sup> See J.Bodurtha and G.Courtadon (1986) for more details.

<sup>14</sup> Another component of transaction costs is given by the bid-ask spread. Unfortu-



Table 2

Description of sample selection from transactions data. European call options

Underlying currency	Original data			Total deletion			Data used in study		
	observations	trades	contracts	observations	trades	contracts	observations	trades	contracts
Australian dollar	680	1025	126448	186	272	35165	494	753	91283
British pound	612	993	43483	176	306	14671	436	687	28812
Canadian dollar	972	1892	72076	456	885	33349	516	1007	38727
German mark	557	873	32889	117	171	5744	440	702	27145
Japanese yen	398	702	30660	89	169	6009	309	533	24651
Swiss franc	682	1294	125635	80	137	6660	602	1157	118975
TOTAL	3901	6779	431191	1104	1940	101598	2797	4839	329593

#### 4 Estimation of the variance-covariance matrix of exchange and interest rates

A key variable in the option pricing model defined in the second section is the volatility of the underlying currency. The investor who can overcome the difficulties in estimating the volatility and get the best estimate will most likely also get the greatest profit. There exist at least two alternative estimates for the volatility of exchange rates: a historical standard deviation (HSD) and an implied standard deviation (ISD).

A first approximation of the volatility can be obtained by using past data. The historical volatility is estimated based on a sample of the  $n$  latest observations on spot exchange rates, and is calculated as follows:

$$HSD = \sqrt{\frac{\sum_1^n (R - \bar{R})^2}{n - 1}} * \sqrt{p} \quad (4)$$

nately, option bid-ask prices are not available after September 30, 1983. Therefore, the option trade price must be used in our tests.

where  $R = \ln S_t / S_{t-1}$ ,  $\bar{R} = 1/n \sum_1^n R$ ,  $n$  is the number of past prices,  $\tilde{p}$  is the adjustment to obtain annualized volatility, depending on the frequency of data used,  $S_t$  is the spot exchange rate on date  $t$ ,  $S_{t-1}$  is the spot exchange rate on date  $t - 1$ .

The number of prices used depends arbitrarily on the investor's estimation or strategy. It can be equal to 20, 30, 40, 60 etc. However, the minimum number of days used is 10, in order to prevent any large bias. In the case of the daily data, the  $\tilde{p}$  is equal to 360 calendar days or 250 trading days. The choice is also arbitrary.

Another method for estimating the volatility is to use the market's opinion of the future variance of the asset. This opinion is contained in the market price of the option. By taking the market price of the option, an investor can work backwards through the pricing formula, using an iterative, trial and error process, to obtain the volatility that is implicit within that option price. In the case of the Garman and Kohlhagen model (G&K) the implied standard deviation ISD is calculated for each observation using an empirical Newton-Raphson interpolation with the relevant model, eqs (1). A maximum of 30 iterations are carried out in the calculation.

In the model with stochastic interest rates (SIR) the ISD are computed using the ISD from G&K model adjusted to include the variances and covariances of interest rates from equation (2) when  $k = 0$  and  $\lambda_{\max}^2 = \lambda_{\min}^2 = \hat{\sigma}^2$ . The Implied Standard Deviations in the model with transaction cost (TC) are calculated applying the ISD from G&K model when  $\lambda_{\max}^2 = \sigma_s^2 [1 + k + \frac{k\sqrt{2/\pi}}{(\sigma_s\sqrt{\Delta t})}]$ . In the case of the model with stochastic interest rates and transaction costs (SIR&TC) we use the ISD from G&K model modified as shown by equation (2).<sup>15</sup>

Table 3 presents the averages and standard deviations of the implied volatility for the Garman and Kohlhagen model and Transaction Costs model. The implied volatility is given on an annual basis. It is a non-weighted mean calculated with a whole sample. The transaction costs model is computed for  $k = .002$  and a revision period equal to one day,  $\Delta t = 1/250 = .004$ . In this case the revision of hedging portfolio is effectuated once a day.

<sup>15</sup> We use the maximum volatility,  $\lambda_{\max}^2$ , which puts the upper bound on an option price.



Table 3

Summary statistics for estimates of implied volatility ISD

Underlying currency	Sample size	<i>G&amp;K</i> Model	<i>G&amp;K</i> Model Standard Deviation	TC Model	TC Model Standard Deviation
		Mean		Mean	
Australian dollar	494	.0725	.028	.0842	.0283
British pound	436	.0845	.0202	.0963	.0204
Canadian dollar	516	.0328	.0143	.0434	.0150
German mark	440	.1140	.0295	.1260	.0297
Japanese yen	309	.1180	.0341	.1302	.0343
Swiss franc	602	.1802	.0527	.1926	.0528

From table 3 we note that in all cases, the implied volatility computed from the basic model (*G&K*) is higher than the volatility inferred from the model with transaction costs. It seems obvious as the transaction costs are positive.

Using the stochastic interest rate component in our model implies an estimation of the variance of interest rates for the six foreign currencies ( $\sigma_r^2$ ) and the US dollar ( $\sigma_r^2$ ), covariance of interest rate for each currency and US interest rate ( $\sigma_{r+r}$ ), covariance of foreign exchange and interest rates ( $\sigma_{sr}$ ), and covariance of exchange rate and US interest rate ( $\sigma_{sr}$ ).

The average exchange and interest rates for the six currencies and the mean of US interest rate are given in the table 4. The table 5 presents covariance matrices.

Table 5 shows that estimated covariances of exchange rates and foreign interest rates (foreign from the US point of view) are positive for the Australian dollar, the British pound, the Canadian dollar and the Japanese yen. A positive covariance means that if the foreign interest rate (Eurocurrency seven days interest rates) goes up, the exchange rate of foreign currency (expressed in \$ per unit of foreign currency) also goes up. The German mark and the Swiss franc exhibit a negative covariance of foreign exchange rate and foreign interest rate.

The variance of domestic interest rate (US) is higher than any other variance of foreign interest rate and much higher than covariances of domestic (US) and foreign interest rates.



Table 4  
Average exchange and interest rates<sup>a,b</sup>

Underlying Currency	Exchange rate Mean	Interest Rate Mean
Australian dollar	.78 (0.036)	.132 (.0239)
British pound	1.74 (0.1172)	.125 (.024)
Canadian dollar	.84 (0.0261)	.108 (.0179)
German mark	.58 (0.0455)	.065 (.0196)
Japanese yen	.007 (0.00048)	.059 (.0165)
Swiss franc	.68 (0.0605)	.063 (.027)
US dollar	1	.078 (.0174)

<sup>a</sup>Exchange rate is in \$ per unit of foreign currency.

<sup>b</sup>The standard deviations are in parentheses.

Moreover, table 5 shows that the estimated covariance of exchange and foreign interest rates for the Australian dollar, the British pound, the Canadian dollar and the Japanese yen exceeds that of exchange and domestic interest rates (US).

Table 5  
Variance - covariance matrix (annualized data on 250 days basis)

Underlying currency	Exchange rate						Interest rate						
	AuD	BrP	CaD	GeM	JaY	SwF	AuD	BrP	CaD	GeM	JaY	SwF	USD
I Australian dollar	.00007						.0793						
t British pound		.000047						.0501					
e Canadian dollar			.000002						.0373				
r German mark				-.00023						.0497			
s Japanese yen					.00003						.0693		
a Swiss franc						-.00018						.1211	
e US dollar													
	-.000053	-.00001	-.00001				-.0006	-.003		.0045			.29
	.000015	.000035	.000027				.0027	.0207			.0008		

This means that the conditional variance,  $\hat{\sigma}^2$ , in the model with stochastic interest rates exceeds the corresponding estimate in the con-

stant interest rate model.<sup>16</sup>

For the German mark and the Swiss franc the situation is ambiguous and a sign of the difference between stochastic and constant volatility depends on the time to maturity,  $T$ , of an option.

## 5 Predicting volatility

In this section, following Scott and Tucker (1989) and Frankel and Wei (1991), we test the hypothesis that the market-anticipated standard deviation is an unbiased estimator of the actual exchange rate volatility. To test this hypothesis we consider the following regression:

$$ASD_{t+1} = \alpha_1 ISD_t + \alpha_0 + e_{t+1} \quad (5)$$

where  $ASD_{t+1}$  is actual standard deviation from  $t$  to  $t+1$ ,  $ISD_t$  is the standard deviation implied in the option price observed in the market at time  $t$ , and  $\alpha_0$  is a constant.

The ASD and ISD are expressed in monthly series computed from daily data (exchange rates and option prices) from the third Wednesday of the month (expiration settlement date) to the third Wednesday of the following month. An actual standard deviation (ASD) is a historical standard deviation (HSD) estimated on an *ex-post* basis. To compute ASD's series, we use the HSD's formula with  $n = 20$  and  $\tilde{p}$  equal to 250 days. In the case of the TC, SIR and SIR&TC models these series are modified to include stochastic interest rates and transaction costs. The TC and SIR&TC models are used with an assumption that the hedging portfolio is adjusted once a day ( $\Delta t = 0.004$ ) and the round trip transaction cost  $k$  is equal, as always, to 0.2%. The ISDs are computed as a non-weighted average from European call option prices which have 26 – 35 days to a given maturity date.<sup>17</sup>

The null hypothesis for our regression is  $H_0: \alpha_1 = 1$  and  $\alpha_0 = 0$ .

The results of regression (5) for the six exchange rates are reported in table 6.

<sup>16</sup> In other terms, the difference between stochastic interest rate volatility and constant interest rate volatility is greater than zero:  $\hat{\sigma}^2 - \sigma_s^2 = \frac{T^2}{3}(\sigma_r^2 + \sigma_{r^*}^2 - 2\sigma_{rr^*}) + T(\sigma_{sr^*} - \sigma_{sr}) > 0$ .

<sup>17</sup> The use of call options with exactly 30 days to next maturity date would be more appropriate. Unfortunately, in the case of European options, these calls are scarce.

Table 6

Regression of actual volatility (ASD) on implied volatility (ISD):

$$ASD = \alpha_0 + \alpha_1 ISD.^{ab}$$

Underlying currency		<i>G&amp;K</i> Model	<i>TC</i> <sup>c</sup> Model $\Delta t = 1D$	<i>SIR</i> Model	<i>SIR&amp;TC</i> <sup>c</sup> Model $\Delta t = 1D$
Australian dollar	$\alpha_0$	.04 (.049)	.055 (.05)	.004 (.048)	.055 (.049)
	$\alpha_1$	.875 (.474)	.888 (.48)	.902 (.466)	.915 (.471)
	$R^2$	.1	.1	.11	.11
	$n$	33	33	33	33
British pound	$\alpha_0$	.042 (.032)	.0582 (.033)	.0457 (.033)	.061 (.033)
	$\alpha_1$	.817 (.31)	.827 (.313)	.805 (.31)	.815 (.315)
	$R^2$	.188	.189	.182	.183
	$n$	32	32	32	32
Canadian dollar	$\alpha_0$	.0127 (.011)	.026 (.012)	.0156 (.0125)	.029 (.013)
	$\alpha_1$	.807 (.131)	.848 (.138)	.807 (.15)	.845 (.157)
	$R^2$	.565	.565	.50	.50
	$n$	31	31	31	31
German mark	$\alpha_0$	.134 (.039)	.150 (.039)	.142 (.04)	.159 (.041)
	$\alpha_1$	-.13 (.262)	-.131 (.264)	-.186 (.273)	-.188 (.276)
	$R^2$	.01	.01	.018	.018
	$n$	27	27	27	27
Japanese yen	$\alpha_0$	.032 (.035)	.048 (.035)	.03 (.035)	.046 (.035)
	$\alpha_1$	.72 (.24)	.725 (.25)	.745 (.241)	.753 (.243)
	$R^2$	.3	.3	.32	.32
	$n$	22	22	22	22
Swiss franc	$\alpha_0$	.139 (.032)	.157 (.032)	.142 (.032)	.159 (.033)
	$\alpha_1$	-.117 (.367)	-.118 (.370)	-.118 (.375)	-.119 (.379)
	$R^2$	.006	.006	.006	.006
	$n$	19	19	19	19

<sup>a</sup>The ISD and ASD are computed on the 250 days basis.<sup>b</sup>Standard errors are given in parentheses.<sup>c</sup>The TC and SIR&TC models are given for the maximal value of volatility ( $\sigma_{\max}$ ).

Results in table 6 indicate that standard deviations implied in currency options prices are valuable predictors of future currency return variance for four currencies: the Australian dollar, the British pound, the Canadian dollar and the Japanese yen. For these currencies the  $\alpha_1$  coefficients are positive and the null hypothesis  $H_0 : \alpha_1 = 1$  is not rejected at the 5% level. The  $\alpha_1$  coefficients are negative for the German



mark and the Swiss franc and the null hypothesis  $\alpha_1 = 1$  is rejected at the 5% level. The Australian dollar exhibits the highest  $\alpha_1$  coefficients, in the case of SIR&TC model the  $\alpha_1$  is equal to 0.915.

The examination of the constant term  $\alpha_0$  and its statistical significance indicates that for the Australian dollar, the British pound and the Japanese yen in four models tested, the  $\alpha_0$  coefficients are not different from zero at the 5% level of significance. For the German mark and the Swiss franc the opposite occurs: all  $\alpha_0$  coefficients are different than zero at the 5% level. In the case of the Canadian dollar the null hypothesis  $H_0 : \alpha_0 = 0$  is not rejected at 5% level for the Garman and Kohlhagen model and SIR model, but it is rejected when we use the TC and SIR&TC models.

Two other results are apparent from table 6. First, the coefficients of determination  $R^2$  are relatively low for all currencies, only for the Canadian dollar  $R^2$  is greater than 0.50. It may imply a prudent interpretation of  $\alpha$  coefficients. Second, among the four models presented, the model with stochastic interest rates (SIR&TC) exhibits the highest predictive ability of future standard deviations whilst the constant interest rate model (G&K) exhibits the lowest predictive capacity.<sup>18</sup> The  $\alpha_1$  coefficients in the SIR&TC model are in general closer to 1 than the  $\alpha_1$  coefficients in the G&K model, and the absolute value of  $t$  test are smaller for the SIR&TC model.

The regression analysis is reapplied employing the historical standard deviation (HSD) as a second explanatory variable.

$$ASD_{t+1} = \alpha_0 + \alpha_1 ISD_t + \alpha_2 HSD_t + e_{t+1} \quad (6)$$

As indicated by the results reported in table 7, historical parameters improve slightly the predictive accuracy. Actually, almost all coefficients  $\alpha_1$  are improved in regression (6) with respect to regression (5). The Australian dollar always has the highest  $\alpha_1$  coefficients, and in the case of SIR&TC model it is equal to 0.945.

For all six currencies and for all four models, at the 5% level of significance, we do not reject the null hypothesis that the coefficient  $\alpha_2$  is equal to zero;  $H_0 : \alpha_2 = 0$ .

<sup>18</sup> Unfortunately, because of the fact that the number of observations used in the regressions is relatively low, some caution is in order before interpreting the results. In fact, it is commonly assumed that the sample size should be at least equal to 30 which is not the case for the three currencies: the German mark, the Japanese yen and the Swiss franc (only 19 observations).

Table 7

Regression of actual volatility (ASD) on implied volatility (ISD) and historical volatility (HSD):  $ASD = \alpha_0 + \alpha_1 ISD + \alpha_2 HSD^{ab}$

Underlying currency		G&K Model	$TC^c$ Model $\Delta t = 1D$	SIR Model	$SIR \& TC^c$ Model $\Delta t = 1D$
Australian dollar	$\alpha_0$	.046 (.05)	.061 (.05)	.046 (.049)	.062 (.05)
	$\alpha_1$	.903 (.484)	.915 (.49)	.932 (.476)	.945 (.481)
	$\alpha_2$	-.082 (.183)	-.082 (.185)	-.089 (.180)	-.088 (.182)
	$R^2$	.105	.105	.115	.115
British pound	$\alpha_0$	.043 (.033)	.045 (.033)	.0589 (.033)	.0612 (.0335)
	$\alpha_1$	.725 (.491)	.75 (.494)	.733 (.497)	.758 (.5)
	$\alpha_2$	.0648 (.265)	.039 (.266)	.066 (.268)	.04 (.27)
	$R^2$	.19	.183	.19	.183
Canadian dollar	$\alpha_0$	.0129 (.011)	.0263 (.0117)	.0196 (.0127)	.033 (.0132)
	$\alpha_1$	.816 (.18)	.858 (.19)	.663 (.2)	.693 (.214)
	$\alpha_2$	-.013 (.166)	-.014 (.175)	.036 (.189)	.039 (.198)
	$R^2$	.565	.565	.425	.424
German mark	$\alpha_0$	.0844 (.036)	.101 (.037)	.097 (.0386)	.113 (.039)
	$\alpha_1$	-.131 (.247)	-.132 (.249)	-.187 (.262)	-.188 (.265)
	$\alpha_2$	.423 (.21)	.428 (.21)	.389 (.222)	.393 (.224)
	$R^2$	.155	.155	.13	.13
Japanese yen	$\alpha_0$	.038 (.035)	.053 (.036)	.04 (.036)	.055 (.036)
	$\alpha_1$	.885 (.31)	.89 (.31)	.865 (.31)	.873 (.32)
	$\alpha_2$	-.222 (.25)	-.222 (.25)	-.203 (.25)	-.203 (.25)
	$R^2$	.33	.33	.32	.32
Swiss franc	$\alpha_0$	.131 (.032)	.148 (.032)	.132 (.033)	.148 (.033)
	$\alpha_1$	-.16 (.38)	-.160 (.39)	-.17 (.388)	-.17 (.39)
	$\alpha_2$	.113 (.2)	.114 (.2)	.138 (.2)	.14 (.201)
	$R^2$	.026	.0262	.035	.035

<sup>a</sup>The ISD and ASD are computed on 250 days basis.

<sup>b</sup> Standard errors are given in parentheses.

<sup>c</sup>The TC and SIR&TC models are given for the maximal value of volatility ( $\sigma_{max}$ ).

This result is consistent with the notion that currency option traders incorporate information about historical standard deviations when setting market prices. It is consistent with results reported by



Bodurtha and Courtadon (1986), Shastri and Tandon (1985), and Scott and Tucker (1989), that the currency options market appears efficient in this respect.

Similarly, with regards to the Australian dollar, the British pound, the Canadian dollar and the Japanese yen, the coefficients of determination  $R^2$  improve slightly; only in the case of the German mark and the Swiss franc do they increase more (but they are still very low).

In this section, we investigated a strong version of the rationality of the market in forming its *ex ante* anticipation of the one-month-ahead exchange rate volatility inferred from call currency options. We find that in OLS estimations, the strong rationality is rejected only with regards the German mark and the Swiss franc. For the four other currencies: the Australian dollar, the British pound, the Canadian dollar and the Japanese yen we find that the standard deviation implied in currency options prices is a valuable predictor of future currency return variance. These results are different from those obtained by Wei and Frankel (1991). Wei and Frankel reject the strong rationality for all the currencies studied (the British pound, the German mark, the Swiss franc, the Japanese yen) and argue that the implicit volatilities extracted from options prices in the standard way are not optimal forecasts of future volatilities.

However, the differences in results can be explained by:

- *different methodology:*  
Wei and Frankel apply the Garman and Kohlhagen formula to American call options and we use this model modified to include stochastic interest rates and transaction costs to value European call options,
- *different periods:*  
the study of W&F covers the period from February 1983 to January 1990 whereas our option data base begins in December 1987 and extends through to September 1991,
- *different interest rates:*  
W&F use the 3-month Treasury Bill rate for the United States and call money rates for other four countries whilst our interest rates are seven-days Eurocurrency interest rates,

- *different sample size:*  
in their regressions, Wei and Frankel use a sample of 85 observations and we have only 19-33 observations available.

## 6 Conclusion

In this paper, we apply the Tamborski option pricing model with stochastic interest rates and transaction costs to investigate the rationality of the market in forming its *ex ante* anticipation of the one-month-ahead exchange rate volatility inferred from call currency options. We examine a strong version of the rational expectations, in other words, whether the implied standard deviation is an unbiased predictor of the future realized standard deviation. We find that in OLS estimations, the strong rationality is rejected only for the German mark and the Swiss franc. In regards to the four other currencies, the Australian dollar, the British pound, the Canadian dollar and the Japanese yen, we find that the standard deviation implied in currency options prices is a valuable predictor of future currency return variance. These results are different from those presented in Wei and Frankel (1991). Wei and Frankel reject the strong rationality for the all currencies studied (the British pound, the German mark, the Swiss franc, the Japanese yen) and argue that the implicit volatilities extracted from options prices in the standard way are not optimal forecasts of future volatilities. It would appear that the principal reason for the differences is due to the fact that they apply the Garman and Kohlhagen model to American call options while we use the Garman and Kohlhagen model modified to include stochastic interest rates and transaction costs in the case of European call options. Three other sources of the differences in results are: the different periods, different interest rates and different size of data set used in our study.



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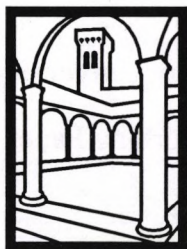
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