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Research Paper 310 August 2012

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Yang Chang and Erik Schlögl

ISSN 1441-8010 www.qfrc.uts.edu.au

Carry Trade and Liquidity Risk: Evidence from Forward and Cross-Currency Swap Markets*

Yang Chang and Erik Schlögl

Finance Discipline Group, University of Technology, Sydney

Draft version: August 2012

Abstract

This study empirically examines the effect of foreign exchange (FX) market liquidity risk and volatility on the excess returns of currency carry trades. In contrast to the existent literature, we construct an alternative proxy of liquidity risk - violations of no arbitrage bounds in the forward and currency swap markets. We also use volatility smile data to capture FX-market specific volatility. The sample data cover periods both before and after the Global Financial Crisis (GFC). Both proxies are significant in explaining the abnormal returns of carry trades, particularly after the GFC. Our findings provide substantial evidence that uncovered interest parity (UIP) puzzle can be resolved after controlling for liquidity risk and market volatility.

Keywords: uncovered interest rate parity, carry trade, liquidity risk, no-arbitrage bound, volatility

JEL Classfication: F31, G15

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*We are grateful for helpful comments from Dr. Kristoffer Glover.

1. Introduction and Motivation

1.1 Introduction

This paper empirically tests the effect of liquidity risk and volatility in the FX market on the performance of currency carry trades. In a carry trade investors borrow funds in a low-yield currency (funding currency) and lend the funds in a high-yield currency (investment currency) to gain the interest rate differential between the two currencies. The uncovered interest parity (UIP) predicts that the carry should be exactly offset by the depreciation of the investment currency. If UIP holds in practice, carry trades should have zero return. In practice, UIP often fails and investment currencies have been found to actually appreciate on average against funding currencies, this has been termed the UIP puzzle. The failure of UIP has also been referred to as the "forward discount puzzle" (Fama, 1984). The UIP puzzle is the reason that carry trades are historically profitable with high Sharpe ratios (Burnside et al., 2011).

Brunnermeier et al. (2008) employ a model with funding liquidity risk to approach the UIP puzzle by studying carry trade performance. In this model carry trades tend to be unwound and incur losses when traders' funding constraints become binding. Therefore proxies for liquidity risk should be significant in explaining carry trade excess returns. These findings provide support for the theoretical liquidity model developed in Brunnermeier and Pedersen (2009). A key result is that after controlling for liquidity risk proxies, the interest rate differential is not significant in predicting carry returns, which points to a potential resolution of the UIP puzzle. However, as criticized in Burnside (2008), the link between the theoretical liquidity model and empirical findings is not sufficiently strong. In particular, the liquidity measures are in general insignificant or marginally significant. Nevertheless Brunnermeier et al. (2008) offers an alternative approach to explaining the UIP puzzle.

1.2 Motivation

We propose that the liquidity measures employed by Brunnermeier et al. (2008), VIX and the TED spread, may not well proxy FX market liquidity risk. Firstly, VIX, which is the implied volatility index for stock options, is not directly related to the FX market. Hence VIX is not an ideal measure of FX market liquidity risk. Secondly, TED spread, the difference between 3-month Eurodollar LIBOR[1] rate and 3-month Treasury-bill rate, is also not specific to the FX market. We conjecture that these proxies may have caused the lack of statistical significance. We therefore are motivated to identify alternative proxies of FX market liquidity risk to tackle the UIP puzzle. In addition, we build upon the theoretical liquidity model of Brunnermeier and Pedersen (2009) and allow for the effect of market volatility.

We develop an FX market specific proxy for liquidity risk - violations of no arbitrage bounds in the forward and currency swap markets, which measures market expectation of future liquidity risk. Since the GFC, cross currency basis swaps (hereafter 'currency swap') have been quoted with substantially larger basis spreads than before. A currency swap contract exchanges floating interest rates of two different currencies at each tenor of the swap term, notional amounts are also exchanged based upon the spot exchange rate at initiation. By the no-arbitrage pricing principle, two floating rates should trade at par and the basis spread should be zero (Hull, 2008). In practice, a basis is often added to the floating rate (usually with LIBOR as the reference rate) of the left-hand side (LHS) currency. For instance, from the late 1990s until August 2007, the basis of the one-year EUR/USD swap ranged from 0 to 2.5 basis points (Baba et al., 2008). However, since the end of August 2007, the basis added to 3-month EURIBOR[2] turned significantly negative. From the collapse of Lehman Brothers in September 2008 to February 2010, the average basis was minus 34 basis points (Source: Bloomberg). This means that USD borrowers pay the 3-month USD LIBOR flat but receive 3-month EURIBOR minus 34 basis points.

It has been observed in the literature that there is a shortage of USD liquidity in the global banking industry and the USD funding gap is especially large for European banks. Fender and McGuire (2010) and McGuire and Peter (2009) note that European banks' total USD-denominated assets were more than 800 billion by mid-2007. European banks have traditionally used short-term USD borrowing to fund long-term assets. Since the GFC, it became

[1]London Interbank Offered Rate is the rate at which banks borrow unsecured funds in the London interbank lending market. Source: www.bbalibor.com

[2]The unsecured borrowing rate for Eurozone banks in the Euro interbank market.

increasingly difficult to borrow USD in the unsecured interbank market. European banks relied more on the swap market and there was a huge demand for USD. However, the demand of USD from European banks is not matched by the demand of EUR from US counterparts. Due to the heightened liquidity risk of USD, European banks had to pay a price for the demand and the price was reflected in the large and negative basis added to EURIBOR. Although Japanese banks had smaller USD funding gap than European banks, the basis of JPY/USD currency swap also turned negative. There is anecdotal evidence that non-Japanese banks raised funds in JPY and swapped into USD. Hence the relative demand of USD over JPY may also have dislocated during the crisis. To provide more liquidity of USD, the US Federal Reserve established swap lines with major central banks, including ECB, SNB, BoE and BoJ[3] (Baba and Packer, 2009).

The basis spreads prior to the crisis were small and arbitrage opportunities exploiting the spreads could be largely canceled by transaction costs. From an arbitrageur's point of view, there are two main transaction costs in currency swaps: the spread of LIBOR-LIBID[4] and the bid-offer spread of the forward exchange rate. An arbitrageur in the interbank market has to pay LIBOR when borrowing funds but only gets LIBID when lending funds. The arbitrageur also must pay the offer price of the forward exchange rate when buying foreign currency but can only sell at the bid price. If spreads in interest rates and forward exchange rates are sufficient to cancel the arbitrage profit, the basis in currency swaps should be bounded by some function of interest rates and forward rates. We include transaction costs and derive bounds for the forward rates and currency swap basis rates, which should eliminate arbitrage opportunities in practice. By construction, we propose that this proxy incorporates both market liquidity risk and funding liquidity risk. Market liquidity risk is captured by transaction costs, i.e. bid-ask spreads, whereas funding liquidity risk is proxied by the magnitude of violations of the no-arbitrage bounds. In this study we specifically examine if this alternative liquidity proxy can better explain the UIP puzzle by testing its effect on carry trade excess returns.

[3]European Central Bank, Swiss National Bank, Banks of England and Bank of Japan.

[4]London Interbank Bid Rate is a bid rate at which a bank is willing to borrow from other banks, while LIBOR is the ask rate.

To allow for the effect of volatility specific to the FX market, we use volatility smile data from the FX option market. Volatility smile information represents practitioners' views of future volatility of the underlying exchange rate until the option maturity. We propose that this proxy should have a significant effect on explaining exchange rate movement and hence carry trade return.

Our sample data cover periods both before and after the GFC because both liquidity risk and market volatility have substantially heightened since the GFC. It is thus interesting to investigate if there are structural breaks in the effects of our proposed proxies. Econometric test results demonstrate that both proxies have significant effects on carry trade performance, particularly after the GFC. Furthermore, the interest-rate differential is not significant in predicting carry trade returns after controlling for volatility and liquidity, hence providing a potential resolution of the UIP puzzle.

The remainder of the paper is organized as follows. Section 2 reviews related literature. Section 3 describes the data and methodologies used for our econometric tests. Section 4 presents and analyzes results and section 5 concludes.

2. Review of Related Literature

The UIP puzzle is among the most prominent puzzles in international economics and finance, see Engle (1996) for a comprehensive survey. Original works on the failure of UIP date back to Hansen and Hodrick (1980), who reject the FX market efficiency hypothesis that speculations in the FX forward market should have zero return. Meese and Rogoff (1983) find that exchange rates can be modelled by a "random walk" and investors are able to exploit interest rate differentials between currencies. Fama (1984) labels the failure of UIP as "forward discount puzzle".

Among more recent works, Chinn and Meredith (2004) find that UIP fails at short-run horizons but recovers at long-run horizons and they attribute the failure of UIP to the interaction of random FX market shocks with endogenous monetary policy reactions. Lustig and Verdelhan (2007) assert that conditional upon the interest-rate differential, aggregate consumption growth risk is useful in explaining the UIP puzzle. Burnside (2007) challenges the results in Lustig and Verdelhan (2007) by arguing that the covariance between the excess portfolio return and risk factors is not significant. Instead, Burnside et al. (2011) approach the UIP puzzle by studying the properties of carry trades. They argue that the high average payoff to carry trades reflects a "peso problem"[5] and is uncorrelated with traditional risk factors.

Brunnermeier and Pedersen (2009) propose a theoretical model that links market liquidity and funding liquidity. Market liquidity is defined as the ease of trading securities in the market and funding liquidity is the ease of raising funds. When highly leveraged traders suffer losses they get margin calls from lenders. Traders have little own capital to meet the margin call and funding liquidity worsens. This is the "margin spiral". On the other hand, fire-sales increase volatilities and move security prices away from fundamental values and traders suffer further losses on existing positions. Traders have to sell more, leading to further price drops. This is the "loss spiral". These two spirals are destabilizing and market liquidity and funding liquidity reinforce each other such that liquidity can suddenly dry up. Brunnermeier and Pedersen (2009) use this liquidity model to explain some stylized facts, including the correlation between market liquidity and volatility. They also predict that speculative investments have negative skewness, arising from the asymmetric response to liquidity shocks: shocks leading to losses are amplified through liquidity spirals and shocks leading to gains are not amplified.

Built upon the theoretical liquidity framework, Brunnermeier et al. (2008) approach the UIP puzzle by examining the performance of carry trades. They propose that carry trades tend to be unwound when speculators near their funding constraints. The unwinding of carry trades results in large losses and currency crashes. Key findings in Brunnermeier et al. (2008) include: 1) In the short-run, carry trades are profitable due to under-reaction to shocks to interest rate differentials. The initial under-reaction arises from liquidity frictions in the market and speculative capital arrives slower than predicted by UIP (Mitchell et al., 2007). However, in the long-run, speculators tend to over-react and bubbles are built in exchange rates. Abreu and Brunnermeier (2003) argue that bubbles build up due to dispersion of opinions and the need

[5] Peso problem refers to the situation that in an investment there is a high probability of small gains, and a small probability of large losses.

for coordination among arbitrageurs, hence a "synchronization" problem. 2) Carry trade crashes are positively correlated with funding liquidity measures: VIX and TED spread. 3) Controlling for liquidity effects, the interest rate differential is not significant in forecasting the excess returns of carry trades, which helps resolve the UIP puzzle.

As commented in Burnside (2008), a model with liquidity frictions is a plausible candidate to explain the UIP puzzle, particularly when empirical evidence fails to support other leading explanations. In this respect, Brunnermeier et al. (2008) provides support for the liquidity model proposed by Brunnermeier and Pedersen (2009). On the other hand, the lack of statistical significance of liquidity measures, especially TED spread, implies that these measures may be improved to gain more quantitative success. For example, in the panel regression with weekly data, although the sign of the coefficient is correct, the change of TED spread is not contemporaneously significant in explaining excess return of carry trades. The significance is also only marginal with one-week delay. In the panel regression with both interest rate difference and liquidity measures, the liquidity measures are not significant in predicting excess returns for the immediate following quarters.

Among related studies, Ranaldo and Söderlind (2010) use a factor model which captures measures of market volatility and liquidity to study safe haven properties of high-frequency exchange rates. The proxies for volatility are realized exchange rate volatility and VIX. The TED spread is used to measure liquidity. The FX realized volatility is found to be significant in affecting the excess return of all exchange rates in the sample, while VIX is only significant for JPY/USD. The TED spread is not significant for any of the exchange rates. Christiansen et al. (2011) employ a similar factor model to study the risk exposure of carry trade returns. The risk exposures are allowed to be regime-dependent to account for FX time-varying risk premia. As state variables, FX market volatility and TED spread are found to be more significant than VIX and FX market liquidity, which is measured by bid-ask spreads.

3. Data and Empirical Strategies

3.1 Data Description

We collect daily data on four major currencies: USD, EUR, JPY and AUD. The sample period is from January 3, 2006 to August 12, 2011, covering periods both before and after the GFC.

3.1.1 Spot and Forward Exchange Rates

We adopt the Foreign-Domestic (FOR-DOM) quotation style and use USD as the foreign currency and the other three respectively as the domestic currency. For instance, the USD-EUR spot rate is the number of units of EUR for one unit of USD. The data source is Bloomberg. Excluding missing data, there are 1419 trading days during this period. We collect the spot rate and 1-day, 1-month, 3-month, 6-month, 12-month, 2-year, 3-year, 4-year, 5-year forward rates. Because this study explicitly examines the effect of transaction costs, we include the mid, bid and offer rate.

3.1.2 LIBOR/LIBID and Interest Rate Swap (IRS) Rates

We collect USD LIBOR/ LIBID, JPY LIBOR/ LIBID, EURIBOR/EURIBID (source: Bloomberg) and AUD Bank Bill Bid and Offer Rates (source: Reserve Bank of Australia). These rates are selected because they represent the borrowing and lending costs for an arbitrageur in each currency. They are also the references rates used in currency swaps. We use Bank Bill rates to proxy AUD Bank Bill Swap rate (BBSW)[6], which is the reference rate used in AUD currency swaps.

We need IRS rates for two purposes. Firstly, LIBOR/LIBID rates have maturities only out to 12 months. Because LIBOR is often used as the reference rate in an IRS, IRS rates can be used as proxies to extend the LIBOR zero curve beyond 12-month maturity. Secondly, in deriving the bounds for the basis of currency swaps, we eliminate the uncertain cash flow risk by entering an IRS. We use the IRS bid rate to approximate LIBID and the ask rate to approximate LIBOR. IRS data are from Bloomberg.

[6]BBSW data are not available for all maturities and on all trading days. Based upon available BBSW data, we computed the error of using Bank Bill rates to approximate. The average error is 0.3 basis points for 1-month maturity and 0.1 basis points for 3-month rates. The errors are sufficiently small.

We obtain daily data of overnight (O/N), 1-month, 3-month, 6-month and 12-month USD LIBOR/ LIBID, JPY LIBOR/ LIBID and EURIBOR/EURIBID. AUD Bank Bill bid and offer rates are only available for O/N, 1-month, 3-month and 6-month, hence we use one-year AUD IRS rates to proxy. The maturities of IRS data are as follows. USD and JPY: 18-month, 2-year, 3-year, 4-year and 5-year; EUR: 2-year, 3-year, 4-year and 5-year; AUD: 1-year, 2-year, 3-year, 4-year and 5-year. Maturities vary for different currencies due to different payment frequencies of IRS rates and data availability. USD, JPY and AUD swap rates are paid semi-annually and EUR swap rates are paid annually.

3.1.3 Currency Swap Basis

Daily data of currency swap basis rates, including mid rate, pay rate and receive rate. Maturities are 1-year, 2-year, 3-year, 4-year and 5-year. We have three pairs of currency swaps. For each pair, the left hand side (LHS) currency and the right hand side (RHS) currency are respectively EUR-USD, JPY-USD and AUD-USD.

3.1.4 FX option volatility smile

At-the-money volatility ($ATMVOL$), risk reversal (RR) and butterfly (BF) provide us with three measures of FX market volatility. $ATMVOL$ measures the market expectation of future volatility of underlying exchange rate, while RR and BF respectively measures the skewness and kurtosis of the volatility smile (Wystup, 2006). We collect the most liquid 1-month $ATMVOL$, 25-delta RR and 25-delta BF data from Bloomberg.

3.2 Empirical Methodologies

3.2.1 Liquidity Basis

We calculate no-arbitrage bounds for forward rates and currency swaps and define the violation magnitude of bounds as liquidity basis. The maturities of liquidity basis include 1-month, 3-month and 6-month for forward rates and 1-year, 2-year, 3-year, 4-year and 5-year for currency swaps. Notations are as follows:

X_0: spot mid price of FOR-DOM at time 0;
$F_{(0,t)}$: forward mid price of FOR-DOM at time 0 with maturity t;
X_{bid}: spot bid price of FOR-DOM at time 0;
X_{offer}: spot offer price of FOR-DOM at time 0;
$F_{bid(0,t)}$: forward bid price of FOR-DOM at time 0 with maturity t;
$F_{offer(0,t)}$: forward offer price of FOR-DOM at time 0 with maturity t;
$r_{LIBOR(0,t)}$: domestic currency annual LIBOR rate between time 0 and t;
$r_{LIBID(0,t)}$: domestic currency annual LIBID rate between time 0 and t;
$\overline{r}_{LIBOR(0,t)}$: foreign currency annual LIBOR rate between time 0 and t;
$\overline{r}_{LIBID(0,t)}$: foreign currency annual LIBID rate between time 0 and t;
$\tau_{(0,t)}$: year fraction of time 0 to t;

Let $[0, T]$ be the term of the currency swap, i.e. time 0 is initiation and T is maturity. Also t_i (i =1, 2 ,..., n, where $t_n = T$) denotes a pre-specified set of interest payment exchange dates, i.e. tenors.

Bounds for Forward Exchange Rates

In order to make riskless profit, an arbitrageur must engage in transactions simultaneously in both the domestic and the foreign market. The arbitrageur can borrow funds at domestic LIBOR, the strategy is as in Table 1.

Table 1: Arbitrage Strategy

Initiation	**Maturity t**
borrow unit of domestic currency	$-(1 + r_{LIBOR(0,t)}\tau)$
sell at $\frac{1}{X_{offer}}$ and invest at $\overline{r}_{LIBID}$	
forward contract and lock in F_{bid}	$\frac{1}{X_{offer}}(1 + \overline{r}_{LIBID(0,t)}\tau)F_{bid(0,t)}$

At maturity, to ensure no-arbitrage the net-cash flow must be non-positive,

$$\frac{1}{X_{offer}}(1 + \overline{r}_{LIBID(0,t)}\tau)F_{bid(0,t)} - (1 + r_{LIBOR(0,t)}\tau) \leq 0 \qquad (1)$$

Hence we have,

$$F_{bid(0,t)} \leq \frac{X_{offer}(1 + r_{LIBOR(0,t)}\tau)}{1 + \overline{r}_{LIBID(0,t)}\tau} \qquad (2)$$

This is the upper bound for the bid price of the forward exchange rate. Alternatively, the arbitrageur can start from borrowing the foreign currency and the arbitrage strategy is as in Table 2.

Table 2: Arbitrage Strategy

Initiation	Maturity t
borrow unit of foreign currency	$-(1+\overline{r}_{LIBOR(0,t)}\tau)$
sell at X_{bid} and invest at r_{LIBID}	
forward contract and lock in $\frac{1}{F_{offer}}$	$X_{bid}\frac{(1+r_{LIBID(0,t)}\tau)}{F_{offer(0,t)}}$

The no-arbitrage condition requires that,

$$X_{bid}\frac{(1+r_{LIBID(0,t)}\tau)}{F_{offer(0,t)}} - (1+\overline{r}_{LIBOR(0,t)}\tau) \leq 0 \tag{3}$$

Hence we must have,

$$F_{offer(0,t)} \geq \frac{X_{bid}(1+r_{LIBID(0,t)}\tau)}{1+\overline{r}_{LIBOR(0,t)}\tau} \tag{4}$$

This is the lower bound for the offer price of the forward rate. We propose that bound (2) and (4) must hold to eliminate arbitrage opportunities.

Bounds for Basis of Currency Swaps

A generic currency swap is quoted as: LHS currency LIBOR + B/ RHS currency LIBOR. B is the basis added to the LHS currency LIBOR. The pay rate BP is the price that a market maker (MM) is willing to pay when receiving the RHS currency LIBOR. The receive rate BR is the price that a MM receives when paying the RHS currency LIBOR. BR is always higher than BP and the difference is the profit for the MM. Let Y denote the RHS LIBOR-LIBID spread and Z denote the LHS LIBOR-LIBID spread. Assume that principal amount is 1 unit of RHS currency for 100 units of LHS currency (e.g. LHS is JPY and RHS is USD).

If one counterparty receives LHS LIBOR + BP and pays RHS LIBOR, then at initiation it receives the RHS principal 1 and pays the LHS principal 100. The LHS principal is borrowed at LHS LIBOR and the RHS principal is invested at RHS LIBID. The cash flows are summarized in Table 3.

Table 3: Arbitrage Strategy

cash flow	**initiation**	**each tenor t_i**	**maturity T**
positive	RHS 1	LHS LIBOR + BP, RHS LIBID	LHS 100
negative	LHS 100	RHS LIBOR, LHS LIBOR	RHS 1

We see that the principal amounts cancel and the net cash flow position at every tenor is (LHS principal * BP) - (RHS principal * Y). BP is a fixed quantity and conventionally Y is fixed at 12.5 basis points for all currencies quoted by British Banker Association (Coyle, 2001). The no arbitrage condition requires that the total present value (PV) of these cash flows must not be greater than zero. To properly discount we convert all cash flows to a common currency, say RHS currency and use RHS LIBID as the discount rate. We use LIBID because the arbitrageur should discount cash flows at the investment rate. The PV is calculated as,

$$\sum_{i=1}^{n}\left\{(\frac{\text{LHS principal} * BP}{F_{offert_i}} - \text{RHS principal} * 12.5\text{bps})d_{t_i}\right\} \tag{5}$$

In (5) d_{t_i} is the discount factor applicable between time 0 and t_i. $\frac{1}{F_{offert_i}}$ is the price investors have to take when selling LHS for RHS in the forward market. We firstly solve,

$$\sum_{i=1}^{n}\left\{(\frac{\text{LHS principal} * BP}{F_{offert_i}} - \text{RHS principal} * 12.5\text{bps})d_{t_i}\right\} = 0 \tag{6}$$

for BP. Suppose BP_0 is the solution. By market convention, the spot mid rate X_0 at initiation is equal to the ratio of LHS principal over RHS principal, we hence simplify Eq. (6) as,

$$\sum_{i=1}^{n}\left\{(\frac{X_0 * BP_0}{F_{offert_i}} - 12.5\text{bps})d_{t_i}\right\} = 0 \tag{7}$$

Solving Eq. (7) for BP_0 we obtain,

$$BP_0 = \frac{\sum_{i=1}^{n}(12.5\text{bps} * d_{t_i})}{X_0 * \sum_{i=1}^{n}\frac{d_{t_i}}{F_{offert_i}}} \tag{8}$$

Because for any $BP \leq BP_0$ the no-arbitrage condition holds, BP_0 is the upper bound for the basis pay rate. The upper bound has been derived by assuming Y is constant. If the spread is not fixed, the net position is exposed to uncertain cash flows. To eliminate this risk, we propose an alternative strategy. The counterparty can enter an IRS contract in the RHS currency. In this swap, the counterparty pays fixed RHS interest rate and receives RHS LIBOR. Let H denote the fixed rate of the IRS, cash flows are summarized in Table 4.

Table 4: Arbitrage Strategy

cash flow	**initiation**	**each tenor t_i**	**maturity T**
positive	RHS 1	LHS LIBOR+BP, RHS (LIBOR + LIBID)	LHS 100
negative	LHS 100	RHS LIBOR, LHS LIBOR, H	RHS 1
net cash flow		LHS 100 * BP + RHS 1 * (LIBID - H)	

RHS LIBID in the net cash flow is uncertain. However we can view this series of cash flows as a floating rate bond without notional payment at maturity. Hence we know that the PV of this bond is RHS principal $*(1 - d_{t_n})$. We thus eliminate the uncertainty and the PV of total net cash flows is,

$$\text{RHS principal} * (1 - d_{t_n}) + \sum_{i=1}^{n}\left\{(\frac{\text{LHS principal} * BP}{F_{offert_i}} - \text{RHS principal} * H)d_{t_i}\right\} \tag{9}$$

Setting (9) equal to zero and solving for BP_0 we obtain,

$$BP_0 = \frac{\sum_{i=1}^{n}(H * d_{t_i}) + d_{t_n} - 1}{X_0 * \sum_{i=1}^{n}\frac{d_{t_i}}{F_{offert_i}}} \tag{10}$$

The other counterparty of the swap pays LHS LIBOR + BR and receives RHS LIBOR. The cash flow position is in Table 5.

Table 5: **Arbitrage Strategy**

cash flow	**initiation**	**each tenor** t_i	**maturity** T
positive	LHS 100	RHS LIBOR, LHS LIBID	RHS 1
negative	RHS 1	LHS LIBOR + BR , RHS LIBOR	LHS 100
net cash flow		- LHS 100 (BR + Z)	

The no arbitrage condition is,

$$\sum_{i=1}^{n} -(\text{LHS principal} * (BR + Z) * d_{t_i}) \leq 0 \tag{11}$$

Because LHS principal and the sum of discount factors must be both positive, if Z is fixed at 12.5 bps, we must have,

$$BR \geq -12.5\text{bps} \tag{12}$$

Hence -12.5 bps is the lower bound for the basis receive rate. Alternatively, we can follow a similar IRS strategy if Z is not fixed. Assume the IRS swap fixed rate is G for the LHS currency, the lower bound would then be,

$$BR \geq \frac{1 - d_{t_n}}{\sum_{i=1}^{n} d_{t_i}} - G \tag{13}$$

3.2.2 Discount Curves with LIBOR (LIBID) Rates

To test whether no-arbitrage bounds hold, we build two discount curves: one based upon LIBOR with IRS ask rates and the other upon the LIBID with IRS bid rates. We rewrite the forward exchange rate bounds (2) and (4) as,

$$F_{bid(0,t)} \leq \frac{X_{offer} \times \overline{d}_{LIBID(0,t)}}{d_{LIBOR(0,t)}} \tag{14}$$

$$F_{offer(0,t)} \geq \frac{X_{bid} \times \overline{d}_{LIBOR(0,t)}}{d_{LIBID(0,t)}} \tag{15}$$

where $\overline{d}_{LIBOR(0,t)}$ ($\overline{d}_{LIBID(0,t)}$) represents the foreign currency LIBOR (LIBID) discount curve while $d_{LIBOR(0,t)}$ ($d_{LIBID(0,t)}$) represents the domestic currency LIBOR (LIBID) discount curve. We construct discount curves out to the 12-month maturity. Simply compounded LIBOR (LIBID) rates are firstly converted to continuously compounded rates,

$$LIBOR_c = \frac{1}{\tau} \times \ln(1 + LIBOR \times \tau) \tag{16}$$

The continuously compounded discount factor then is,

$$d_{LIBOR(0,t)} = \exp(-LIBOR_c \times \tau(0,t)) \tag{17}$$

3.2.3 Discount Curves with Interest Rate Swap Rates

Discount curves beyond one year and out to five-year maturity are extracted from par swap rates. An IRS can be considered as a contract in which a coupon bearing bond is exchanged for a floating-rate bond (Brigo and Mercurio, 2006). Because the initial value of an IRS must be zero to preclude arbitrage and floating-rate bonds always trade at par, the par swap fixed rate is simply the coupon rate for a par-value coupon bond. Assuming unit notional amount, swap fixed rate S_{t_N} must satisfy,

$$(S_{t_N} \times F) \times \sum_{i=1}^{N} d_{t_i} + d_{t_N} = 1 \tag{18}$$

where F is the payment frequency of the swap rate and N is the total number of coupon payments. From Eq. (18) we obtain the final discount factor,

$$d_{t_N} = \frac{1 - (S_{t_N} \times F) \times \sum_{i=1}^{N-1} d_{t_i}}{1 + (S_{t_N} \times F)} \tag{19}$$

To apply Eq. (19), we need all discount factors and swap rates before the final maturity, i.e. from t_1 to t_{N-1}. We use the bootstrapping method with linear interpolation,

$$S_t = S_{t_i} + (\frac{t - t_i}{t_{i+1} - t_i}) \times (S_{t_{i+1}} - S_{t_i}), t_i < t < t_{i+1} \tag{20}$$

and work iteratively with Eq. (20) to obtain d_{t_N}.

3.2.4 Specifications of Model Variables

We follow Brunnermeier et al. (2008) and calculate the carry trade return in excess of the return predicted by UIP, hence the abnormal return. We use USD as the foreign currency in all three pairs. In each currency carry trade, USD is the funding currency. Hence funds are borrowed at the USD money market rate and invested at the EUR, JPY and AUD interest rates respectively. The daily excess return Z_t^k is thus,

$$Z_t^k = (r_{t-1}^k - r_{t-1}^{USD}) - (S_t^k - S_{t-1}^k) \tag{21}$$

In Eq. (21) S_t^k is the logarithm spot exchange rate at the end of day t for currency k and r_{t-1}^k is the logarithm overnight money market rate at the end of day $t-1$ for currency k. Hence the excess return is equal to the interest rate differential between currency k and USD locked in at the end of day $t-1$, minus the return of the spot rate from day $t-1$ to t. The term $S_t^k - S_{t-1}^k$ stands for the depreciation of currency k against USD. The UIP predicts that the interest rate differential $r_{t-1}^k - r_{t-1}^{USD}$ should be exactly offset by the depreciation of currency k, hence $E_{t-1}(Z_t) = 0$. The UIP puzzle arises from empirical observations that the abnormal return Z_t^k is often positive, i.e. investment currencies do not depreciate as much as predicted by UIP, instead in many cases they appreciate against the funding currency.

We conjecture that the liquidity bases of different maturities are closely related to each other because they are driven by some common liquidity events. These bases are not sufficiently independent of each other and from a statistical point of view, it is sensible to include all maturities in our empirical tests. Since there are 8 maturities, in order to reduce dimensionality we employ the principal component analysis (PCA) to transform these closely related variables into uncorrelated new variables.

3.2.5 Econometric Model

To test the effects of liquidity risk and volatility on the excess return of carry trades, we propose a linear factor autoregressive distributed lag (ADL) model for each currency pair (i.e. USD/JPY, USD/EUR and USD/AUD),

$$Z_t = \beta_0 + \beta_1 Z_{t-1} + \beta_2 IRDIFF_{t-1} + \beta_3 ATMVOL_t + \beta_4 ATMVOL_{t-1} + \beta_5 RR_t + \beta_6 RR_{t-1} + \beta_7 BF_t + \beta_8 BF_{t-1} + \beta_9 BS_t + \beta_{10} BS_{t-1} + \epsilon_t, \tag{22}$$

where Z_t is the abnormal return of carry trade between day $t-1$ and t, $IRDIFF_{t-1}$ is the overnight interest rate difference at the end of day $t-1$ between the investment currency and USD, $ATMVOL_t$, RR_t and BF_t are respectively the ATM volatility, 25-delta risk reversal and 25-delta butterfly at the end of day t for the 1-month FX option, quoted as USD/investment currency. Lastly, BS_t is the liquidity basis based on PCA at the end of day t. We include one-day lags to account for potential autocorrelations in the exchange rates. The inclusion of lags in the regression model also enables us to capture both inertia of the dependent variable and contemporaneous effects. If the lags are significant, explanatory variables will also have some extent of predictive power for the exchange rate movement.

Compared to related literature (Brunnermeier et al., 2008, Ranaldo and Söderlind, 2010), variables in our regression model may better proxy FX-market liquidity risk and volatility. Firstly, ATM volatility, risk reversal and butterfly represent FX option market practitioners' expectations. Therefore they should better measure FX market volatility. Secondly, we replace TED spread with liquidity basis of forward exchange rates and currency swaps, which captures both market liquidity and funding liquidity risks specific to the FX market.

We make several hypotheses with respect to the effects of explanatory variables. Firstly, the effect of ATM volatility is negative if the investment currency on average depreciates against USD when FX market volatility increases. Secondly, risk reversal is negatively correlated with Z_t because FX options in our study are quoted as USD/investment currency. If RR increases, then the USD call is more favored than the USD put, hence the market expects that the investment currency depreciates against the USD. Thirdly, we take an agnostic view on butterfly because higher BF indicates larger movements of exchange rates towards either direction. Fourthly, we expect that liquidity basis negatively impacts carry return if carry traders unwind positions when liquidity risk increases, hence suffering losses. Finally, after controlling for these factors, if $IRDIFF$ is not significant in affecting carry returns, we may resolve the UIP puzzle.

The ADL model in Eq. (22) is used to test effects of explanatory variables for each individual currency pair. In order to control for individual currency heterogeneity we also construct panel data, which combine both time series of all variables in the ADL model and cross-sectional elements, namely three currency pairs. The panel technique we employ is the currency-fixed effects model.

4. **Empirical Results**

4.1 Liquidity Basis

We firstly calculate no-arbitrage bounds of 1-month, 3-month and 6-month forward rates and 1-5 year currency swap basis spreads with the formulae developed in the previous section[7]. Violations of no-arbitrage bounds are calculated as: 1) upper bound minus forward bid rate (currency swap basis pay rate) and 2) forward offer rate (currency swap basis receive rate) minus the lower bound. Negative results mean that bounds are violated and arbitrage opportunities are present. The findings are presented in Figures 1 to 6 for forward rates and in Figures 7 to 12 for currency swaps. For ease of illustration, only 1-year, 3-year and 5-year swaps are presented[8].

In the forward market, we find that for both USD-EUR and USD-JPY currency pair, the upper bound of the forward bid rate holds strongly. The curves in Figures 1 and 3 were very stable before the GFC. From the second half of 2007 it has fluctuated but remained significantly positive. On the other hand, in Figures 2 and 4 the lower bound test shows almost a mirror image. Before the crisis, it held tightly. Starting from the crisis, the lower bound has been violated for most of the period.

[7] Investors tend to hedge FX risks with forward contracts for maturities less than one year. For terms greater than or equal to one year, currency swaps provide greater liquidity.
[8] Complete results are available upon request.

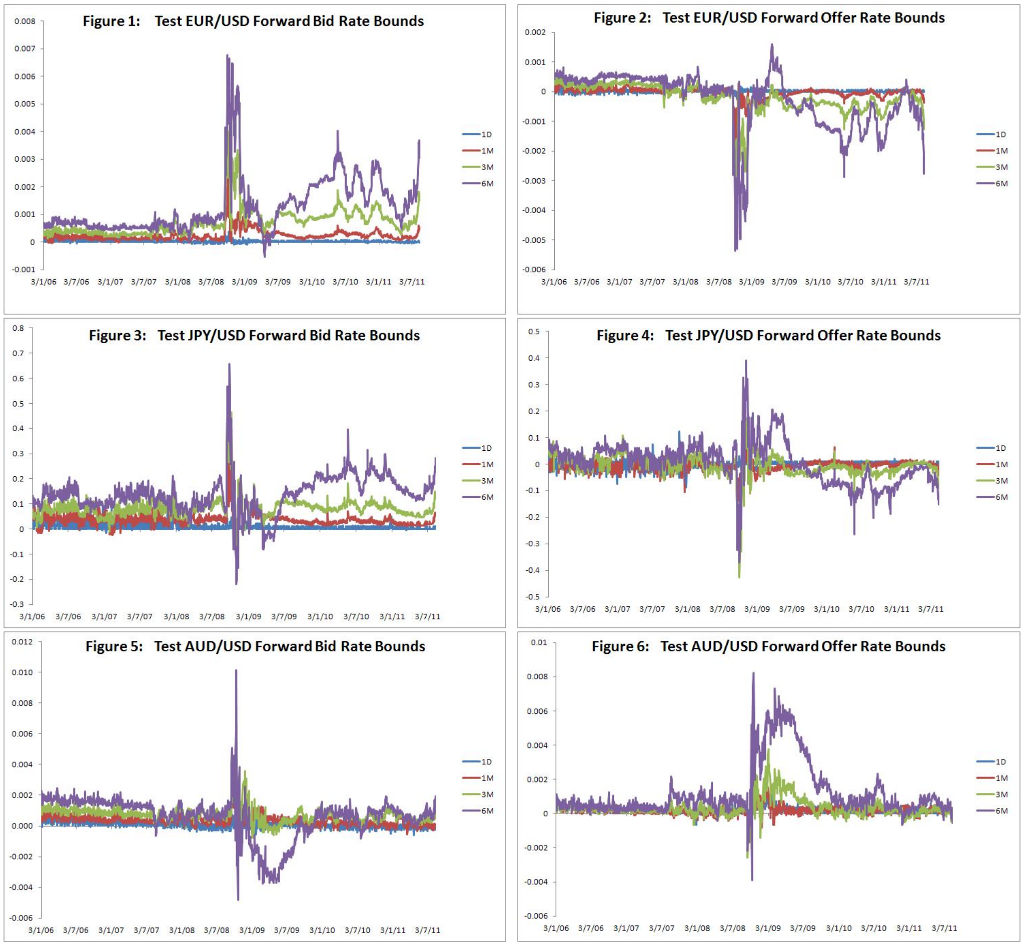

Fig.1-6. Violations of no-arbitrage bounds of forward exchange rates. In Fig. 1, 3 and 5 the violations are calculated as the difference between the upper bound of the forward bid rate and the quoted forward bid rate. In Fig. 2, 4 and 6 the violations are calculated as the difference between the quoted forward offer rate and the lower bound of the forward offer rate. Positive parts of the graphs indicate that there are no arbitrage opportunities considering transaction costs. Negative parts of the graphs indicate that arbitrage opportunities are present in the forward market, after considering transaction costs.

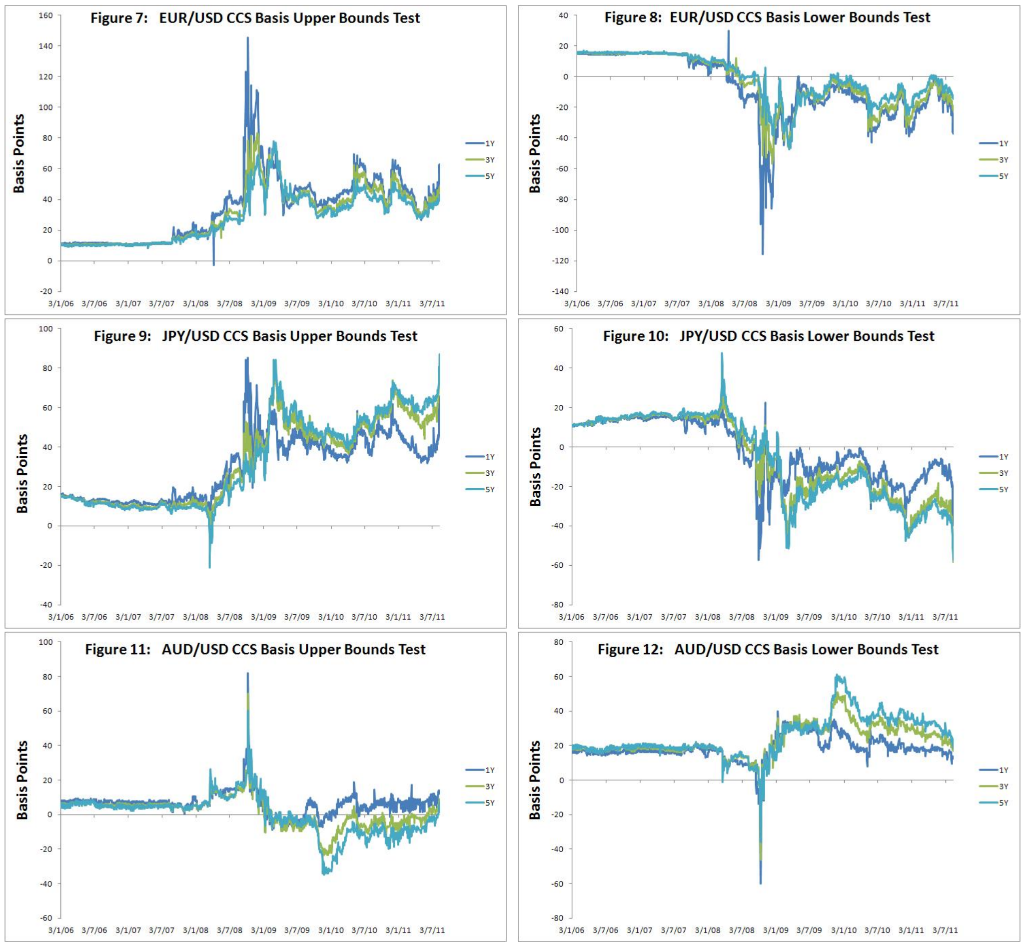

Fig.7-12. Violations of no-arbitrage bounds of currency swap basis rates. In Fig. 7, 9 and 11 the violations are calculated as the difference between the upper bound of the currency swap basis pay rate and the quoted pay rate. In Fig. 8, 10 and 12 the violations are calculated as the difference between the quoted receive rate and the lower bound of the currency swap basis receive rate. Positive parts of the graphs indicate that there are no arbitrage opportunities considering transaction costs. Negative parts of the graphs indicate that arbitrage opportunities are present in the currency swap market, after considering transaction costs.

The USD-AUD forward rate bounds behave differently. In Figures 5 and 6 we see both upper and lower bounds held strongly before the crisis. During 2009 the upper bounds of forward bid rates were violated. Since the beginning of 2010 the upper bounds have generally held. After a relatively short period of violations (roughly from August to November 2008), the lower bounds have held on a majority of trading days. The findings in currency swaps are very similar. The upper bounds of EUR/USD and JPY/USD swaps hold but lower bounds are significantly violated since the GFC. On the other hand, the upper bounds of AUD/USD swap are violated since the crisis but lower bounds generally hold.

The bound violations contradict the no-arbitrage methodology in pricing forward rates and currency swaps. Clearly the persistence of the observed bound violations demonstrate that the market has not taken advantage of the apparent opportunities. We propose that the market is prevented from doing so by increased market imperfections, in particular the currency liquidity risk. These imperfections have developed in the forward and spot currency market since the GFC and result in forward and currency swap prices being determined by supply and demand pressures, rather than by arbitrage considerations.

In this study all forward rates are quoted as the price of one unit of USD, hence if supply exceeds demand, the market maker could buy the contract at a lower rate than the no-arbitrage level, hence the upper bound of the bid rate holds even tighter. On the other hand, the market maker can afford to sell at a level lower than the no-arbitrage lower bound. We therefore propose that the lower bound of the offer rate can be violated if supply exceeds demand. This implies demand for USD in the forward market is lower relative to the demand in the spot market, which is consistent with the USD liquidity risk. The USD funding shortage during the crisis faced by European and Japanese institutions has driven demand to secure USD in the spot market, hence the demand for USD is relatively lower in the forward market. On the other hand, the upper bound violations of the AUD forward bid rate indicate lower demand for USD in the spot market compared to the forward market, but higher demand for AUD in the spot market than in the forward market. This is also consistent with the observation that Australian banks do not have USD funding shortage and instead have high demand of AUD funding in international markets (Ossolinski and Zurawski, 2010). The supply/demand imbalance argument also applies in currency swaps. Since the crisis, in the currency swap market the demand for USD borrowing far exceeds demand for EUR and JPY, hence the lower bounds of EUR/USD and JPY/USD currency swap basis receive rates are substantially violated. The violation of the upper bound of AUD/USD currency swap basis pay rates implies that demand for AUD exceeds the demand for USD.

Standard theories in finance, such as Arbitrage Pricing Theory (Ross, 1976), propose that arbitrageurs exploit violations of arbitrage free prices and no-arbitrage equilibria should be quickly restored. However, under extreme market circumstances, arbitrage is risky and ineffective (Shleifer and Vishny, 1997). We propose that liquidity risk is a plausible factor which may render arbitrage strategies ineffective. During the crisis, banks face a liquidity squeeze and are reluctant to make lending to LIBOR counterparties for longer than three months (Mollenkamp and Whitehouse, 2008).

4.2 Principal Component Analysis and Summary Statistics

Table 6 shows the results of PCA based upon the correlation matrix for the liquidity basis. The first principal component explains 67.17%, 84.42% and 59.26% of total variance of liquidity basis for JPY, EUR and AUD respectively. The factor loadings on the first principal component all take positive values and are approximately equally weighted for maturities beyond one year. In order to reduce dimensionality and ease the interpretation, we take the first principal component as the common factor.

Table 6: Principal Component Analysis

	JPY	EUR	AUD
Eigenvalue number 1	0.6717	0.8442	0.5926
Factor loadings			
Maturity	PC 1	PC 1	PC 1
1M Basis	0.1194	0.2932	0.1168
3M Basis	0.2556	0.3543	0.1842
6M Basis	0.2546	0.3221	0.2101
1Y Basis	0.4126	0.3783	0.4214
2Y Basis	0.4224	0.3784	0.4468
3Y Basis	0.4176	0.3719	0.4428
4Y Basis	0.4097	0.3645	0.4136
5Y Basis	0.4059	0.3568	0.4050

Table 7, 8 and 9 show the summary statistics of each variable in the ADL regression model Eq. (22) for each currency pair, both before and after the crisis. We split the full sample period at August 10th of 2007 and treat the period before and after as two sub-samples, in order to capture potential structural breaks in the relationship between carry trade return and explanatory variables. From mid-August 2007 the financial markets started to experience turmoils, such as increasing LIBOR-OIS spreads (Baba and Packer, 2009). Our calculations of liquidity bases also show that in the forward and currency swap markets, the no-arbitrage bounds of JPY and EUR started to be violated around this time[9].

In Table 7 we see that for the USD/JPY pair, all variables show large movements in level and standard deviation after the crisis. For example, the mean of the liquidity basis increased by 55 basis points. The standard deviation of the basis surged to more than 10 times its level before the crisis. Similarly, FX option market volatility variables: ATM volatility, butterfly and risk reversals, also significantly changed in both mean and standard deviation. The interest rate difference substantially decreased after the crisis, due to the stimulatory policies taken by the US Federal Reserve. The carry trade return on average has been profitable after the crisis, due to the much smaller interest rate difference and the substantial appreciation of JPY against USD.

The results are similar in the EUR and AUD summary statistics. The standard deviation of EUR liquidity basis increased about 25 times after the crisis, and about 10 times for AUD basis. FX option volatility measures in both currencies demonstrate much greater variations. In all three currency pairs, most of the variables experienced greater kurtosis, reflecting large market movements and heightened uncertainties since the crisis. Finally, the Jarque-Bera normality tests show that for all the variables (except EUR risk reversal and AUD liquidity basis), the hypothesis of normal distribution is rejected, both before and after the crisis.

The summary statistics clearly show different dynamics of the variables before and after the crisis, which provide us with further motivation to investigate if there exist structural changes.

[9]The AUD bounds violations started from March of 2008.

Table 7: JPY Summary Statistics

Variables	Z	IRDIFF	ATMVOL	BF	RR	BS
Before						
Mean	-0.0001	-0.0479	8.0525	0.1766	-0.9864	-31.23
Median	-0.0007	-0.0482	8.0500	0.1750	-0.8250	-31.84
Maximum	0.0250	-0.0424	11.4750	0.2500	-0.1485	-23.37
Minimum	-0.0160	-0.0526	5.7750	0.1250	-2.5740	-37.24
Std. Dev.	0.0055	0.0019	1.2122	0.0355	0.4714	3.5044
Skewness	0.7506	0.7178	0.2854	-0.1158	-0.8677	0.3851
Kurtosis	4.3516	3.4778	2.4602	1.7887	3.5067	1.9351
Jarque-Bera	69.03	38.72	10.44	25.73	55.29	29.22
Probability	0.0000	0.0000	0.0054	0.0000	0.0000	0.0000
After						
Mean	0.0004	-0.0091	13.2211	0.2892	-2.3635	24.24
Median	0.0003	-0.0013	12.1500	0.2990	-1.9650	32.40
Maximum	0.0538	0.0036	43.0000	0.8787	0.9000	116.86
Minimum	-0.0348	-0.0584	6.3500	0.1260	-10.4000	-76.42
Std. Dev.	0.0081	0.0143	3.9948	0.0771	2.0261	35.7174
Skewness	0.3828	-1.5297	2.3474	2.0217	-1.7958	-0.4714
Kurtosis	6.2908	4.0158	12.0836	15.3900	6.6356	2.1825
Jarque-Bera	481.35	438.19	4408.64	7162.52	1101.28	65.66
Probability	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 8: EUR Summary Statistics

Variables	Z	IRDIFF	ATMVOL	BF	RR	BS
Before						
Mean	0.0003	-0.0193	6.9864	0.1298	-0.1880	-31.69
Median	0.0004	-0.0197	6.9375	0.1250	-0.2000	-31.65
Maximum	0.0177	-0.0110	9.6750	0.1800	0.2500	-28.55
Minimum	-0.0106	-0.0262	4.6500	0.0957	-0.7500	-36.58
Std. Dev.	0.0043	0.0039	1.3141	0.0160	0.1831	1.2618
Skewness	0.4067	0.2218	0.1295	0.1896	0.0658	-0.3058
Kurtosis	4.0785	2.0101	1.8180	2.1343	3.3733	3.1645
Jarque-Bera	30.87	19.91	24.77	15.11	2.65	6.78
Probability	0.0000	0.0000	0.0000	0.0005	0.2657	0.0336
After						
Mean	0.0001	0.0058	12.4031	0.3126	0.7642	25.39
Median	0.0004	0.0040	11.2898	0.2625	0.6840	24.27
Maximum	0.0351	0.0329	29.5000	0.9555	3.3500	156.57
Minimum	-0.0430	-0.0270	6.1500	0.1125	-1.4000	-31.31
Std. Dev.	0.0079	0.0088	3.8731	0.1577	0.8771	31.6158
Skewness	-0.1798	0.2971	1.5265	2.1142	0.5010	0.6381
Kurtosis	5.3384	3.4659	5.5565	6.9245	3.0745	3.9736
Jarque-Bera	236.03	24.04	668.63	1403.36	42.57	108.65
Probability	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 9: AUD Summary Statistics

Variables	Z	IRDIFF	ATMVOL	BF	RR	BS
Before						
Mean	0.0004	0.0089	8.0011	0.1539	0.3913	-39.52
Median	0.0007	0.0097	7.9500	0.1500	0.3750	-39.61
Maximum	0.0189	0.0126	11.5500	0.2004	1.5000	-32.78
Minimum	-0.0246	0.0043	5.9750	0.1250	-0.1750	-45.94
Std. Dev.	0.0054	0.0017	1.1114	0.0145	0.1901	2.3680
Skewness	-0.6296	-0.5062	0.7352	0.9210	0.8852	0.1550
Kurtosis	4.9953	3.1192	3.3047	4.4039	6.4794	2.8169
Jarque-Bera	94.17	17.58	38.14	90.74	257.82	2.19
Probability	0.0000	0.0002	0.0000	0.0000	0.0000	0.3342
After						
Mean	0.0003	0.0379	15.7495	0.3296	2.0029	-54.67
Median	0.0012	0.0418	13.7000	0.3000	1.6813	-56.81
Maximum	0.0724	0.0567	48.5000	0.8250	8.0000	99.11
Minimum	-0.0824	0.0018	8.4936	0.1340	-0.6000	-107.89
Std. Dev.	0.0120	0.0102	6.2230	0.1001	1.4798	22.2220
Skewness	-0.5053	-0.8182	2.2310	1.4285	1.8265	0.6974
Kurtosis	9.5888	2.9997	8.6008	5.5514	6.6963	5.4547
Jarque-Bera	1873.62	112.93	2162.26	618.66	1138.78	336.13
Probability	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

4.3 Unit Root Tests

We perform the Augmented Dickey-Fuller test of unit roots. The tests are taken on both level and first difference of the variables, before and after the crisis. Results are presented in Table 10. The null hypothesis is that the variable has a unit root. The lag length of the test is determined by Schwarz information criterion (SIC) and the probabilities of test statistics are reported.

Table 10 shows that the first differences of all variables are stationary, which is expected for financial time-series data. The carry trade returns are found to be $I(0)$. However, some independent variables are shown to be $I(1)$ at 5% significance level. For example, ATM volatility for all three currencies. The liquidity basis is $I(0)$ only for AUD before the crisis. Taking the first differences of the $I(1)$ variables would avoid the problem of non-stationarity. However, the ADL model aims to capture both the lagged and contemporaneous effects. We therefore choose to use levels of each variable in the regressions. Nevertheless, to address the non-stationarity issue, we will perform robustness checks later in section 4.6.

Table 10: Unit Root Test

	JPY		EUR		AUD	
Before Crisis	Level	1st Diff	Level	1st Diff	Level	1st Diff
Z	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
IRDIFF	0.1218	0.0000	0.4452	0.0000	0.0494	0.0000
ATMVOL	0.3349	0.0000	0.2029	0.0000	0.4616	0.0000
BF	0.0266	0.0000	0.1143	0.0000	0.0010	0.0000
RR	0.2130	0.0000	0.0091	0.0000	0.0001	0.0000
BS	0.2393	0.0000	0.0547	0.0000	0.0313	0.0000
After Crisis						
Z	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
IRDIFF	0.0443	0.0000	0.0456	0.0000	0.0769	0.0000
ATMVOL	0.1119	0.0000	0.0456	0.0000	0.1401	0.0000
BF	0.3332	0.0000	0.3858	0.0000	0.0000	0.0000
RR	0.0700	0.0000	0.0794	0.0000	0.0177	0.0000
BS	0.5567	0.0000	0.0851	0.0000	0.0778	0.0000

4.4 Factor Model Regression Results

Results of the ADL model regression for each currency pair are presented in Table 11, 12 and 13. We firstly run the model for the full sample period. To find if there is a structural break before and after the crisis, we use the Chow Breakpoint Test to identify if parameters are stable over the whole period, with August 10th, 2007 as the break date. Test results[10] show that the break date is supported for JPY and EUR, but not for AUD. As we discussed earlier, AUD reacted to the GFC later than JPY and EUR. Figure 13 shows a plot of AUD bases. We observe that the jump is around observation 560, corresponding to March 18th, 2008 in the sample data. Chow test result supports March 18th, 2008 as the break point for AUD. We hence use August 10th, 2007 for JPY and EUR and March 18th, 2008 for AUD to split the full sample into two sub-periods. The ADL model is then tested for both sub-periods.

[10] To conserve space, results are not presented but are available upon request.

Figure 13: AUD Liquidity Basis

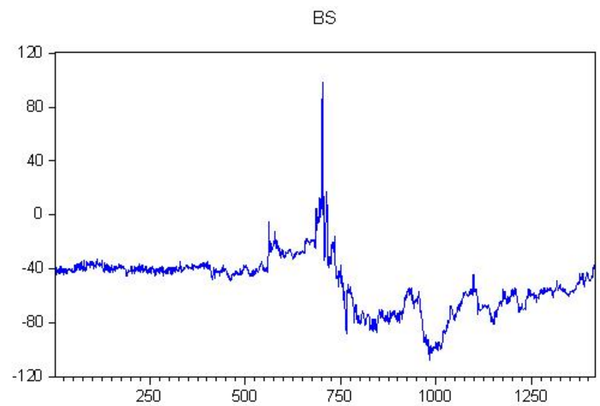

Table 11: JPY Regression Results

	Full Sample		Before Crisis		After Crisis	
Variables	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.
Z(-1)	-0.1180	0.00	-0.1309	0.00	-0.1165	0.00
IRDIFF(-1)	0.0243	0.14	-0.0096	0.94	0.0421	0.03
ATM	0.0024	0.00	0.0057	0.00	0.0023	0.00
ATM(-1)	-0.0027	0.00	-0.0058	0.00	-0.0026	0.00
RR	-0.0104	0.00	-0.0140	0.00	-0.0100	0.00
RR(-1)	0.0096	0.00	0.0128	0.00	0.0090	0.00
BF	-0.0010	0.79	-0.0147	0.03	0.0012	0.76
BF(-1)	0.0046	0.32	0.0040	0.51	0.0056	0.29
BS	0.0000	0.98	0.0003	0.04	0.0000	0.89
BS(-1)	0.0000	0.99	-0.0001	0.34	0.0000	0.96
R-squared	0.4660		0.4760		0.4847	

*Regression results of model (22) for JPY. The dependent variable Z is the carry trade excess return by borrowing USD and investing in JPY. The table presents the regression coefficients and probabilities of test statistics. To account for heteroskedasticity and autocorrelation, the test statistics are based upon Newey-West estimator with two lags. Results are based on daily data. The full sample period is from 01/04/2006 to 08/12/2011. The before crisis period is 01/04/2006 to 08/10/2007 and the after crisis period is 08/12/2007 to 08/12/2011. $IRDIFF$ is the overnight interest rate difference between the JPY and USD. ATM, RR and BF are respectively the ATM volatility, 25-delta risk reversal and 25-delta butterfly for the 1-month USD/JPY option. BS is the liquidity basis based on principal component analysis. (-1) terms are one-day lags.

Table 12: EUR Regression Results

	Full Sample		Before Crisis		After Crisis	
Variables	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.
Z(-1)	-0.1144	0.00	-0.1715	0.00	-0.1070	0.00
IRDIFF(-1)	0.0014	0.93	0.0186	0.85	-0.0225	0.34
ATM	-0.0005	0.41	0.0049	0.00	-0.0009	0.22
ATM(-1)	0.0004	0.51	-0.0049	0.00	0.0008	0.27
RR	-0.0251	0.00	-0.0293	0.00	-0.0243	0.00
RR(-1)	0.0245	0.00	0.0266	0.00	0.0238	0.00
BF	0.0055	0.28	0.0010	0.95	0.0054	0.30
BF(-1)	-0.0071	0.16	0.0027	0.87	-0.0072	0.15
BS	-0.0002	0.00	-0.0001	0.74	-0.0002	0.00
BS(-1)	0.0002	0.00	0.0001	0.42	0.0002	0.00
R-squared	0.3304		0.3118		0.3461	

*Regression results of model (22) for EUR. The dependent variable Z is the carry trade excess return by borrowing USD and investing in EUR. $IRDIFF$ is the overnight interest rate difference between the EUR and USD. ATM, RR and BF are respectively the ATM volatility, 25-delta risk reversal and 25-delta butterfly for the 1-month USD/EUR option. Other specifications are same as Table 11.

Table 13: AUD Regression Results

	Full Sample		Before Crisis		After Crisis	
Variables	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.
Z(-1)	-0.0706	0.00	-0.0497	0.15	-0.0702	0.01
IRDIFF(-1)	-0.0139	0.33	0.0584	0.18	-0.1700	0.00
ATM	-0.0045	0.00	-0.0044	0.00	-0.0043	0.00
ATM(-1)	0.0045	0.00	0.0040	0.00	0.0041	0.00
RR	-0.0126	0.00	-0.0077	0.00	-0.0150	0.00
RR(-1)	0.0123	0.00	0.0082	0.00	0.0151	0.00
BF	-0.0010	0.83	-0.0125	0.11	0.0021	0.73
BF(-1)	0.0056	0.21	0.0184	0.01	0.0009	0.87
BS	-0.0002	0.00	0.0001	0.46	-0.0003	0.00
BS(-1)	0.0002	0.00	-0.0001	0.27	0.0003	0.00
R-squared	0.4543		0.2735		0.5110	

*Regression results of model (22) for AUD. The dependent variable Z is the carry trade excess return by borrowing USD and investing in AUD. $IRDIFF$ is the overnight interest rate difference between the AUD and USD. ATM, RR and BF are respectively the ATM volatility, 25-delta risk reversal and 25-delta butterfly for the 1-month USD/AUD option. March 18th, 2008 is the break date. Other specifications are same as Table 11.

Table 11 results show that in the USD/JPY carry trade, the excess return is significantly negatively correlated with the previous day return. For the post-crisis period, as the interest rate difference between JPY and USD increases, carry return is expected to increase. There is no significance found on $IRDIFF$ for the full period and pre-crisis period. ATM volatility has a significant positive contemporaneous effect on carry return, but this is largely reversed on the next day. Risk reversal is significant for all three periods. As the risk reversal increases, which implies the USD call is placed with a higher volatility than USD put, the carry return of the same day decreases, the effect is almost offset during the following day. Butterfly is significantly negative, but only for the before crisis period. The liquidity basis is only significant for the before crisis period. In both the butterfly and liquidity basis, the one-day lags are not significant.

The EUR regression results in Table 12 show a similar negative effect of the previous day carry return. The interest-rate difference between EUR and USD is insignificant in all three regressions. The ATM volatility effect is only significant before the crisis. The effect of risk reversal is the same as that of JPY. Butterfly is not at all significant. Liquidity basis is not significant before the crisis. However after the crisis its contemporaneous effect on carry return is significantly negative, indicating the pressure of liquidity risk on carry trade performance.

In Table 13, the effect of previous day carry return between AUD and USD is same as the JPY and EUR counterparts. The interest-rate differential is significantly negative after the crisis, but insignificant before the crisis. The ATM volatility effect is significant for all regressions and the reverse effect also is present. However, different from JPY and EUR, the contemporaneous effect of ATM volatility is negative. The findings on risk reversal are the same as JPY and EUR. Butterfly is significant only for the lagged value before the crisis. Similar to EUR, the liquidity basis of AUD is not significant before the crisis, but the effect is significantly negative after the crisis.

We discuss several important findings in the results presented above. Firstly, except for JPY and AUD in the post crisis period, the interest-rate differential at the end of day $t-1$ is not significant in explaining the carry trade excess return at the end of day t. This points to a potential resolution of the UIP puzzle, in which the the interest-rate difference has predictive power for the excess return. Secondly, in general the significant factors show the reverse effect on the following day. The lags typically have opposite signs and magnitudes of the coefficients between t and $t-1$ are very close. The first-order autoregressive model (AR(1)) estimates show that $ATMVOL$, RR, BF and BS all demonstrate high first-order autocorrelation. As pointed out in Ranaldo and Söderlind (2010), this implies if there is no innovation in these terms, the effect on day $t-1$ would be largely reversed on day t. The significance of the lag terms shows some degree of predictive power of these factors. Thirdly, our newly proposed liquidity risk proxy, the liquidity basis, is highly significant for EUR and AUD.

4.5 Panel Regression Results

The individual currency regression results of the ADL model show that the liquidity basis is not significant in the USD/JPY carry trade. This is possibly driven by fundamental differences across currencies. For example, Ranaldo and Söderlind (2010) find that JPY possesses "safe haven" properties. Safe-haven currencies provide hedging benefits during market stress periods. The sharp appreciation of JPY since the GFC offers further support for the haven status of JPY. On the other hand, there is no significant evidence that EUR is a safe-haven currency and AUD generally represents investors' risk appetite. In order to control for currency individual heterogeneity and identify common structures, we test the ADL model with the balanced panel data with currency-fixed effects. The results are summarized in Table 14.

We see in Table 14 that after controlling for currency specific effects, the interest-rate difference is not significant in predicting carry trade excess return, both before and after the crisis. This suggests that the UIP puzzle may be explained after accounting for the effects of FX market volatility and liquidity risk. ATM volatility is insignificant before the crisis, but highly significant after the crisis. Risk reversal is highly significant both before and after the crisis. Butterfly is only significant before the crisis. Lastly, since the crisis the liquidity basis is highly significant. The R^2 increases from 26.32% before the crisis to 35.66% after the crisis, which shows that the break date is reasonably chosen.

Table 14: Panel Regression Results

	Full		Before		After	
Variables	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.
Z(-1)	-0.116816	0.00	-0.136829	0.00	-0.115865	0.00
IRDIFF(-1)	0.006278	0.54	-0.038082	0.59	-0.015416	0.32
ATM	-0.001077	0.00	0.001282	0.10	-0.001178	0.00
ATM(-1)	0.000999	0.00	-0.001568	0.04	0.001084	0.00
RR	-0.019186	0.00	-0.022168	0.00	-0.018914	0.00
RR(-1)	0.018859	0.00	0.020595	0.00	0.018605	0.00
BF	-0.001210	0.69	-0.021721	0.00	-0.000800	0.80
BF(-1)	0.004056	0.16	0.011058	0.13	0.003316	0.28
BS	-0.000143	0.00	0.000067	0.43	-0.000148	0.00
BS(-1)	0.000139	0.00	0.000092	0.28	0.000147	0.00
R-squared	0.341759		0.263211		0.356594	

*This table reports panel regression results with currency-fixed effects. Regression coefficients and probabilities of test statistics are presented. Standard errors are robust to cross-section heteroscedasticity and contemporaneous correlation among cross-sections, with White cross-section method. Results are based on daily data. The full sample period is from 01/04/2006 to 08/12/2011. The before crisis period is 01/04/2006 to 08/10/2007 and the after crisis period is 08/12/2007 to 08/12/2011. Definitions of variables are same as Table 11, 12 and 13.

4.6 Robustness Check

Unit root tests in section 4.3 show that some independent variables are $I(1)$. To address the non-stationarity problem, we estimate both individual currency regressions and the panel regression with the first-differenced values of these variables[11]. Regression results are largely unchanged. For all significant variables in previous regressions, the first-differenced terms are still significant. Even more promisingly, the previously significant interest-rate differentials for JPY and AUD in the post crisis period are no longer significant. Therefore the case for the resolution of the UIP puzzle is even stronger.

5. Conclusion

This paper provides empirical support for a liquidity-risk based model to

[11]Detailed results are available upon requests.

explain the UIP puzzle. We study the effects of liquidity risk and market volatility on the carry trade excess returns. We develop an alternative proxy for FX-market liquidity risk - the violations of no-arbitrage bounds for forward exchange rates and currency basis swaps. We also propose FX market specific volatility proxies. Our hypothesis is that both proxies should be significant in explaining carry trade performance and hence useful for a resolution of the UIP puzzle.

The sample is chosen to cover periods both before and after the GFC in order to capture the structural break. A linear factor model is proposed and tested for both individual currencies and the panel data. Our hypothesis is supported by test results and both proxies are significant. The results are also robust to different specifications of explanatory variables.

We contribute to the extant literature from three perspectives. Firstly, our liquidity risk proxy captures both market liquidity risk and funding liquidity risk. Secondly, we demonstrate that the risk factors change their effects since the GFC. Lastly, we provide significant evidence that the UIP puzzle may be resolved after controlling for liquidity risk and market volatility.

There are two ways in which future research can build upon this study. Firstly, we use high-frequency daily data. It will be interesting to see if results in this study hold for lower-frequency data, such as weekly or quarterly data. Secondly, since the GFC liquidity risk can no longer be assumed negligible, models which embed the liquidity basis should be developed to properly price and hedge FX market contracts.

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