# HEC MONTRÉAL

***Explaining the Returns to the Carry Trade:***
***Currency Crash Risk and Equity Tail Risk***

**par**

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*Mémoire présenté en vue de l'obtention*
*du grade de maîtrise ès sciences en gestion*
*(M. Sc.)*

May 2021

# RÉSUMÉ

Le *carry trade* sur devises est une stratégie exploitant les déviations par rapport à la parité non couverte des taux d'intérêt. Ce mémoire examine deux explications possibles pour rationaliser la profitabilité du *carry trade* appliqué dans les devises du G10. Premièrement, je cherche à déterminer si les rendements de la stratégie peuvent être interprétés comme étant une compensation pour l'exposition au risque de krach. À cette fin, je propose une stratégie pour laquelle l'exposition aux krachs de devises a été couverte (*crash-neutral carry trades*), en utilisant des options de change. Bien que je trouve que les rendements des stratégies couvertes sont inférieurs aux rendements des stratégies non couvertes, ils restent, pour la plupart, positifs et statistiquement significatifs. En accord avec la littérature existante, je démontre qu'une prime de risque de krach peut expliquer, au plus, 19% du total des rendements excédentaires du *carry trade*. Deuxièmement, je cherche à déterminer si les *carry traders* sont rémunérés pour leur exposition au risque extrême du marché boursier. Pour ce faire, j'établis un facteur de risque en utilisant des options sur l'indice S&P 500. Après avoir effectué une analyse de séries temporelles et une analyse transversale, je constate que, bien que les rendements du *carry trade* soient, dans certains cas, exposés à ce facteur, ce dernier n'est pas évalué dans la coupe transversale de rendements sur devises.

**Mots-clés**
*Carry trade* sur devises, options de change, risque de krachs de devises, risque extrême du marché boursier.

# ABSTRACT

The currency carry trade is a trading strategy that exploits violations to the uncovered interest rate parity. This paper examines two possible explanations to rationalize the payoffs to carry trades implemented in the G10 currencies. First, I evaluate whether the excess returns to the strategy can be understood as compensation for exposure to crash risk. To this end, I build crash-neutral carry trades using foreign exchange options, for which the exposure to currency crashes has been hedged. Although I find that the returns to the hedged strategies are lower relative to their unhedged counterparts, they remain, for the most part, positive and statistically significant. In line with the existent literature, I demonstrate that crash risk premia can explain at most 19% of the total carry trade excess returns. Second, I evaluate whether carry traders are being compensated for bearing equity tail risk. To do so, I construct a risk factor using S&P 500 index options. After conducting a time-series and cross-sectional analysis, I find that while the carry trade returns exhibit some exposure to this factor, it is not priced in the cross-section of currency returns.

**Keywords**
Currency carry trade, foreign exchange options, currency crash risk, equity tail risk.

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors, Piotr Orłowski and Valeri Sokolovski, for their ideas, helpful guidance, patience, and time in every step of this thesis.

I would also like to thank my family for their unwavering support and encouragement throughout my studies.

# 1. INTRODUCTION

The currency carry trade is a popular trading strategy in which an investor borrows funds in a low interest rate currency and lends them in a high interest rate currency. According to the uncovered interest rate parity (UIP) theory, the interest rate differential between two currencies should reflect the expected depreciation of the higher interest rate currency against the lower interest rate one. This means that should the UIP hold, an investor engaged in the carry trade wouldn't earn a payoff. Empirically, however, low interest rate currencies tend to depreciate, and high interest rate currencies tend to appreciate. In the literature, this phenomenon is referred to as the "UIP puzzle" or the "forward premium puzzle". Consequently, the carry trade earns positive average excess returns and has been shown to offer higher Sharpe ratios than those associated with the U.S. stock market (Jurek (2014), Burnside, Eichenbaum, Kleshchelski, and Rebelo (2011) and others). I find that over the period from 1985 to 2019, the carry trade implemented in the G10 currencies delivered Sharpe ratios between 0.50-0.80, which are comparable to or better than those of the Fama-French/Carhart equity market factors.

Carry trades also exhibit negatively skewed returns, suggesting that carry traders collect frequent small profits and few large losses when high interest rate currencies suddenly depreciate. Indeed, as mentioned by Brunnermeier, Nagel, and Pedersen (2008), a common saying among traders is that: "exchange rates go up by the stairs and down by the elevator". In line with the literature, I find that the excess returns to the carry trade are strongly negatively skewed over the period from 1985 to 2019. Following Jurek (2014), I investigate whether the excess returns to the carry trade can be understood as being compensation for the exposure to the risk of the rapid depreciation of currencies or crash risk. To do so, I build crash-neutral carry trades using foreign exchange options and compare the excess returns to the hedged and unhedged strategies to establish the crash risk premium. I find that the crash risk premium explains at most 19% of the excess returns to the standard carry trade in contrast with the author, who finds that it accounts for a third of the returns. Therefore, the high returns to the carry trade cannot be rationalized as solely being compensation for bearing currency crash risk.

Given this finding, I turn my attention towards equity market tail risk. Indeed, evidence of a relation between carry trade excess returns and equity downside risk has been demonstrated throughout the literature (Jurek (2014), Caballero and Doyle (2012), Lettau, Maggiori, and Weber (2014) and others). I seek to determine whether carry trade returns can be explained by investors being compensated for the exposure to this risk. To this end, I build an option trading strategy to proxy for aggregate equity market jump risk, as presented in Cremers, Halling, and Weinbaum (2015). I find evidence that the carry trade returns are negatively exposed to this risk, suggesting that losses to the strategy are likely to coincide with tail events in the stock market, such as the 2008 financial crisis. The cross-sectional analysis further reveals a pattern in the loading on equity jump risk; high yield currencies have negative betas while low yield currencies have positive betas. However, the variation in exposures to the jump risk factor does not sufficiently capture the cross-sectional spread in currency returns, and the price of jump risk is not statistically significant. This leads me to conclude that the excess returns to the carry trade cannot be rationalized as being compensation for the exposure to equity tail risk.

This paper contributes to the existing research, firstly, by extending Jurek's (2014) sample beyond 2012 which was relatively soon after the financial crisis of 2008. Furthermore, the literature has not yet reached a consensus on the crash risk hypothesis, and the estimates of crash premia are inconsistent. Therefore, redoing the analysis with an updated sample is worthwhile. As mentioned, the results with the longer sample further disprove the hypothesis, and the crash risk premium explains an even smaller share of the excess returns to the carry trade than what the literature reviewed for this paper suggests. Finally, I examine the relationship between equity tail risk and carry trade returns from a new angle, and test Cremers et al.'s (2015) equity jump risk factor in a foreign exchange context. Although the factor isn't significantly priced in the cross-section of currency returns, I provide additional evidence about the importance of equity market shocks for the global foreign exchange market.

The paper is organized as follows. In Section 2, I provide an overview of the related literature. In Section 3, I define the data used in the subsequent sections of the paper. In Section 4, I present the construction of the standard carry trade portfolio, and its historical performance. In Section 5, I present the construction of the crash-neutral carry trade portfolio, the analysis of the excess returns, and the calculation of the crash risk premium. In Section 6, I evaluate the relation between the carry trade returns and equity market jump risk using both time-series and cross-sectional analysis. Finally, I present my conclusions in Section 7.

# 2. LITERATURE REVIEW

A large body of work attempts to rationalize the high payoffs to the carry trade, and different explanations have been proposed in the literature. This literary review presents some of the most researched explanations. These include that carry trade excess returns reflect compensation for exposure to equity market risk, to foreign exchange market risk, to crash risk, or that they reflect a peso problem.

## 2.1. Risk factors

The most conventional explanation for positive carry trade returns is that investors are being compensated for bearing risk. Indeed, a large body of literature investigates whether carry trade returns can be explained using common equity market risk factors or currency market risk factors.

### *2.1.1. Equity market risk factors*

Many papers evaluate whether standard equity market risk factors, such as the Fama-French (1993) three-factor model can successfully explain the excess returns to the carry trade. Hodrick (2013) finds that that the factors explain very little of the returns to his constructed carry trade strategies. Burnside, Eichenbaum, Kleshchelski, and Rebelo (2008), also find that none of the Fama-French factors covary significantly with the payoffs to their constructed carry trade. Jurek (2014) explores the relation between the returns to his constructed carry trade portfolios and the four Fama-French/Carhart risk factors. The regression results show that all the carry trade strategies' excess returns have a positive relationship with the equity market (*RMRF*) and value (*HML*) factors. In contrast with the other studies, he finds that the regression intercepts are statistically significant at the 10% level or statistically insignificant, suggesting that the model successfully explains the average returns to the carry trade portfolios.

There is also evidence that exposure to the U.S. dollar lowers the explanatory power of equity market risk factors on carry trade returns. In their paper, Daniel, Hodrick, and Lu (2014) evaluate a U.S. dollar-neutral carry trade strategy, as well as a strategy with dollar exposure. When looking at the relation between the returns to both strategies and the Fama-French factors, the results reveal that the model seems to explain the excess returns to carry trades when the portfolio has no direct exposure to the U.S. dollar. However, none of the risk factors significantly explain the carry trade strategy involving dollar exposure; this suggests that exposure to the dollar adds to the enigma of the carry trade's profitability. Bekaert and Panayotov (2019) also arrive at a similar conclusion. Indeed, they build good and bad carry trades employing G10 currencies and evaluate the relation between the Fama-French factors and the returns to these trades. The results demonstrate that these factors fail to explain the average excess returns to the good carry trades, all of which involve the U.S. dollar; this falls in line with observation by Daniel et al. (2014) that exposure to the dollar seems to contribute to the carry trade "enigma". On the other hand, the model is successful at explaining the average excess returns to the bad trades, which do not involve the USD.

*Exposure to equity market downside risk*

Another strand of the literature explores whether the excess returns to the carry trade can be understood as being compensation for exposure to equity market downside risk.

Farhi, Fraiberger, Gabaix, Ranciere, and Verdelhan (2015) find that equity downside risk is significantly priced in the cross-section of carry trade excess returns. Indeed, using risk-reversals[1] on S&P 500 index options, they find that high interest rate currencies tend to depreciate when risk-reversals are high (or when equity disaster risk is high), while low interest rate currencies tend to appreciate during such times.

[1] The risk reversal is a hedging strategy that involves simultaneously selling and buying out-of-the-money put and call options with symmetric strikes; being long a risk-reversal involves being long an out-of-the-money put and short an out-of-the-money call. A positive risk reversal therefore implies the relatively higher implied volatility and price of the put option, and thus the market's anticipation of downturns in the underlying.

Jurek (2014) investigates the relationship between the carry trade portfolio returns and the returns of a mechanical S&P 500 index put-writing strategy (downside risk index, *DRI*)[2]. The *DRI* is exposed to equity market downside risk as the strategy experiences losses when the S&P 500 index declines. The regression of the carry trade returns on the *DRI* yields positive and significant coefficients; losses to the carry trade are likely to coincide with declines of the S&P 500. Furthermore, the regression alphas are statistically insignificant, and in some instances, negative, indicating that after adjusting for the exposure to the *DRI*, carry trades do not offer positive excess returns. These findings suggest that carry trades are exposed to equity market downside risks.

Similarly, Caballero and Doyle (2012) regress the excess returns to their carry trade portfolios on the excess returns to a long position in VIX futures. They find that carry trade returns are negatively correlated with the returns to the VIX rolldown strategy[3], suggesting that carry traders are exposed to downside equity market risk. Furthermore, the regression alphas are, for the most part, statistically insignificant, indicating that after correcting for this exposure, the average excess return to carry trades is very low. The authors also use foreign exchange options to hedge downside risk in their carry trades. Their hedging strategy involves purchasing at-the-money put and call options on exchange rates, according to the investor's position in the currencies used for the carry trade. When performing the same regression using the returns to the hedged carry trade portfolios, they find much smaller beta coefficients than in the previous regression and statistically significant alphas. These results indicate that hedging with foreign exchange options removes much of the carry trade exposure to downside equity market risk, and that the exposure to VIX rolldowns does not explain the average hedged carry trade returns.

Lettau, Maggiori, and Weber (2014) use the downside capital asset pricing model (DR-CAPM) to evaluate whether exposure to downside equity market risk can explain the excess returns to carry trades. They use a two-step estimation process to determine the downside equity market price of risk. After estimating the unconditional beta, and the downside beta, they use the differential between both measures to estimate the price of downside risk. Their results show that the variation in downside betas between low and high interest rate currencies is sufficient to explain the spread in realized returns of said currencies; currencies with more exposure to downside equity market risk yield higher returns. They also determine that the estimated price of downside risk is positive and statistically significant; the DR-CAPM successfully explains payoffs to the carry trade strategy. Dobrynskaya (2014) also determines that the downside market risk CAPM has better explanatory power than the standard CAPM. The author's data and estimation methods differ from those in Lettau et al.

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[2] The *DRI* is developed by Jurek and Stafford (2014). The strategy sells short-dated put options on the S&P 500 index whose strike is one standard deviation below the current index value and places half of the maximum loss (the option strike price) in cash as margin capital.

[3] The VIX rolldown is the strategy of buying the VIX futures contract expiring in two months and selling it after one month passes, to then purchase a new two-month contract to maintain constant exposure to the VIX. This is also referred to as "rolling down the VIX curve". Since the VIX futures curve is generally upwards sloping or in contango, investors engaging in the strategy are buying high, and selling low, generating monthly losses. Holding a long position in VIX futures can be understood as buying insurance against spikes in market volatility. The strategy thus earns a positive return when the VIX increases or the market declines.

(2014), but they reach the same conclusion: excess returns to the carry trade strategy can be understood as being compensation for the exposure to downside equity market risk.

Daniel, Hodrick, and Lu (2014) use the estimates in Lettau et al. (2014) for the price of downside risk to determine if exposure to this risk can explain the returns to their carry trade portfolios. After estimating the differential between the downside and CAMP betas, they multiply this differential with the estimates for the price of downside risk to calculate a downside risk premium. Their results show that the calculated downside risk premia do not significantly explain the average returns to their carry trade portfolios. Their results contradict those obtained by Lettau et al. (2014). They then consider the downside risk index used by Jurek (2014) and its ability to explain the returns to their carry trades, using a similar regression. Their results reveal that while their carry trade portfolios, for the most part, have some exposure to the *DRI*, such exposures are insufficient to explain the returns to the carry trades.

### *2.1.2. Foreign exchange market risk factors*

A large body of literature looks towards the currency market to explain carry trade returns. Indeed, there is evidence that risk measures derived directly from the foreign exchange market are somewhat successful in explaining currency returns.

Lustig, Roussanov, and Verdelhan (2011) show that currency excess returns can be explained by covariances between the returns and risk factors based upon said returns. They build six currency portfolios based on the currency forward discounts relative to the U.S. dollar. After performing a principal component analysis of these portfolios, they find that the first two components explain close to 80% of the total variation in returns on these portfolios. The portfolio loadings on the second component increase monotonically and match the pattern of the cross-section of portfolio excess returns. Based on this principal component analysis, Lustig et al. build two risk factors: the average currency excess return against the USD (*RX*), and the return of a strategy which goes long the portfolio with the highest forward discount and short the portfolio with the lowest one ($HML_{FX}$). The $HML_{FX}$ factor represents the returns to a carry trade strategy and is referred to as the carry trade risk factor; it is strongly correlated with the second principal component. After conducting asset pricing tests, they determine that the $HML_{FX}$ risk factor is priced in the data. Traders investing in high interest rate currencies are compensated for their exposure to carry trade risk, and low interest rate currencies provide a hedge against this risk.

Menkhoff, Sarno, Schmeling, and Schrimpf (2012) study the relationship between global foreign exchange volatility risk and the excess returns to carry trade strategies. They conduct asset pricing tests using five forward-discount sorted currency portfolios as test assets. They use the aggregate foreign exchange market return (*DOL*), similar to the *R*X risk factor in Lustig et al. (2011), and the aggregate foreign exchange volatility innovations (*VOL*) as risk factors. They find that the *VOL* factor is significantly negatively priced in the cross section of carry trade returns. Indeed, the returns to high interest rate currencies co-move negatively with innovations in global foreign exchange volatility, while the returns to low interest rate currencies are positively correlated with volatility innovations indicating that they provide a hedge against the risk.

Finally, Daniel, Hodrick, and Lu (2014) regress the returns to their carry trade portfolios on the two foreign exchange risk factors proposed by Lustig et al. (2011). They find that while both factors, particularly the $HML_{FX}$ factor, have statistically significant explanatory power on the excess returns, they do not explain the average returns, as the regression constants remain highly significant.

In sum, the literature suggests that carry trades involve risk for which investors seek to be compensated. Although risk measures based on the foreign currency market seem to explain carry trade payoffs more effectively than standard equity market risk factors, several studies demonstrate a significant link between equity market downside risk and the payoffs to the carry trade strategy. A downside equity market risk premium could therefore be a viable explanation for carry trade profitability. In this paper, I further explore this using a risk factor constructed from equity option data.

## 2.2. Crash risk and *peso problems*

Another portion of the literature explores the *peso problem* and the crash risk hypotheses. A *peso problem* is a statistical measurement problem by which rational market participants anticipate currency crashes that have not occurred in sample. The *peso problem* hypothesis posits that carry trade profitability is due to the absence or underrepresentation of crashes in the sample, rather than to risk premia. In contrast, the crash risk hypothesis does not attribute the strategy's profitability to a sampling issue. Rather, it posits that the profitability reflects compensation for the exposure to the negative skewness or crash risk that, as shown throughout the literature, characterises the strategy's returns.

### *2.2.1. Peso problems*

To verify the *peso problem* explanation, researchers hedge carry trades against large negative payoffs potentially associated with "peso events", using foreign exchange options. They compare the returns to hedged and unhedged carry trades to determine whether the excess returns to carry trades are due to an overestimation of the probability of crashes occurring. Should the hypothesis hold, the hedged carry trades should have zero returns or significantly smaller returns than the unhedged trades.

Burnside, Eichenbaum, Kleshchelski, and Rebelo (2011) look at the *peso problem* explanation. They use at-the-money foreign exchange options to hedge the carry trades and find that the payoffs to the hedged trades are positive and statistically significant but lower, by about half, than the unhedged carry trade payoffs. These lower returns, according to the authors, provide evidence that the excess returns to unhedged carry trades reflect a *peso problem*. However, they determine that the "peso event" for which investors are being compensated isn't characterized by large negative payoffs to the unhedged carry trades in the peso state. Rather, investors assign high values of the stochastic discount factor to the peso state, which translates into high returns in the non-peso states.

Jurek (2014) uses foreign exchange put options to hedge the carry trade portfolios he builds. The hedged carry trades present statistically significant positive excess returns, which leads him to conclude that a *peso problem* is unlikely to explain the high excess returns in G10 currencies. Jurek attributes the different outcomes of both his and Burnside et al.'s (2011) studies to the options used to hedge the carry trades. Jurek's paper focuses on hedging crash risk using out-of-the-money options, whereas Burnside et al. use at-the-money options. He therefore obtains higher estimates for the mean excess returns to the hedged portfolios, which leads him to reject the *peso problem* explanation. Furthermore, Jurek uses the full set of 45 G10 cross-rate options, whereas Burnside et al. use put and call options against the U.S. dollar to hedge each leg of the carry trade. In his paper, Jurek demonstrates that hedging using X/USD options yields lower excess returns for the hedged carry trades, as the trader pays for exposure to the U.S. dollar risk in each option contract.

Bekaert and Panayotov (2019) also look at the *peso problem* explanation. They hedge the good and bad carry trades, using out-of-the-money foreign exchange put options. Like Jurek (2014), they use the full set of G10 cross-rate options. Their results show that the mean returns to the hedged good and bad carry trades are lower than their unhedged counterparts, but not by much. For all the bad trades, the difference between the hedged and unhedged excess returns is negligible, but it is significant for some of the good trades. Furthermore, their results indicate that hedging improves skewness for good and bad carry trades, but for the good carry trades, there is a substantial decrease in Sharpe ratios after hedging. This implies that the *peso problem* argument could be more applicable to the good trades.

In sum, the research on the *peso problem* interpretation for the excess returns on carry trade provides mixed results. Indeed, the literature reviewed here seems to indicate that carry trades hedged against large losses associated with "peso events", for the most part, exhibit positive and statistically significant returns.

#### *2.2.2. Crash risk*

As mentioned, another explanation for the carry trade excess returns is that they represent compensation for the negative skewness that, as often shown throughout the literature, characterizes the return distribution of these trades. This negative skewness is also referred to as crash risk; it is the risk that the high interest rate currency of the carry trade, or the investment currency, will suddenly depreciate.

Brunnermeier, Nagel, and Pedersen (2008) study the relationship between carry trade excess returns and currency crash risk. Consistent with the literature, they find that the returns to carry trades exhibit negative physical skewness. When looking at the relationship between interest rate differentials and skewness, they find that the differentials predict the negative skewness of currency returns, suggesting that investment currencies are exposed to crash risk. They extend their research by studying the relationship between risk reversals, physical skewness, and returns to carry trades. They find that, while both risk reversals and physical skewness have a negative relationship with interest-rate differentials, their relationships with carry trade returns differ. Indeed, high excess returns on the carry trade predict a more negative future skewness (or an increase in crash risk) but a larger risk reversal (or a lower price of crash risk). This finding points to the possibility that following negative payoffs to carry trades, traders unwind their positions, which in turn lowers crash risk, but they also buy more protection against crash risk, driving up the price of insurance. The authors also try to identify the financial contexts in which currency carry traders are likely to unwind their positions. To do so, they use two measures of funding illiquidity: the CBOE VIX implied volatility index and the TED Spread. They find that carry trades are unwound during increases in the VIX and that the price of insurance against crash risk increases in such times. This suggests that crash risk may be partly driven by traders' changing risk tolerance; it increases during times of low market volatility and vice-versa.

Rafferty (2012) introduces a global currency skewness risk factor that measures crash risk at the aggregate level. He constructs three different types of currency portfolios, one of which is the carry portfolio. Currencies are sorted into five portfolios according to their interest rate differentials relative to the U.S. dollar. Consistent with the literature, the average excess returns, as well as negative skewness, increase monotonically as the interest-rate differential increases. Rafferty considers two risk factors to explain these excess returns: the dollar risk factor (*DOL*), as used by Lustig et al. (2011) and Menkhoff (2012), and the global currency skewness risk factor (*SKEW*). As defined by Rafferty, *SKEW* is a measure of the intramonth skewness of exchange rate changes for a group of investment currencies relative to a group of funding currencies. This measure becomes negative if the group of high interest rate currencies depreciates considerably relative to the group of low interest rate currencies. After conducting asset pricing tests on the excess returns to their carry portfolios, their empirical results reveal a pattern: when global currency skewness becomes more negative, the returns to holding high interest currency portfolios increase. This points to *SKEW* being a risk factor that explains the returns to the carry portfolios. Rafferty explains that foreign exchange investors may require higher premiums when investing in high interest rate currencies, as they may be worried about the sudden depreciation of these currencies, which may force them to unwind their positions quickly. Low interest rate currencies have lower expected returns, as they offer a hedge against periods of increased global negative skewness.

In an effort to quantify a crash risk premium, Jurek (2014) hedges carry trades using the full set of 45 G10 out-of-the-money foreign exchange put options. He demonstrates that, conditional on the absence of *peso problems*, the difference between the mean returns to the unhedged and hedged portfolios provides an estimate of the crash risk premium. His results demonstrate that the excess returns to the hedged carry trades have less negative skewness when compared to the unhedged carry trades. The mean returns to the hedged carry trades are positive and significant but lower than those of the unhedged carry trades. When comparing them to obtain the crash risk premium, the results reveal that it accounts for, at most, a third of the excess returns to the carry trades in his sample.

In the same paper cited earlier, Farhi, Fraiberger, Gabaix, Ranciere, and Verdelhan (2015) construct an exchange rate model which incorporates both Gaussian (or normal) and disaster risk (or the risk of large currency crashes). They use a two-step estimation method to estimate world disaster risk premia in the ten most developed currency markets. According to their results, disaster risk premia in their sample are statistically significant. Farhi et al. also construct hedged carry trades. Doing this, they find that while disaster risk has significant explanatory power on carry trade returns, it does not explain the totality of the returns. Indeed, the put options hedge the disaster risk present in carry trade returns but partially hedge the Gaussian risk. Therefore, a carry trader still earns significant excess returns, even after hedging against crash risk. They find that disaster risk premia account for more than a third of carry trade excess returns, slightly higher than the results found by Jurek (2014). Chernov, Graveline, and Zviadadze (2010) also aim to quantify crash risk present in currency returns using a similar model to Farhi et al. (2009) that takes into account normal and crash risk. They find that crash risk makes up for around 25% of the total currency premium.

Finally, in their paper, Bekaert and Panayotov (2019) disprove the crash risk explanation for carry trade returns. They construct good and bad carry trades based on a Sharpe ratio benchmark. Their results show that skewness can be dramatically improved by eliminating certain currencies from the carry trades while not affecting profitability. Indeed, good carry trades have relatively high Sharpe ratios and slightly negative or positive skewness when compared to the standard carry trade. This implies that negative skewness, or crash risk, can be diversified away, and carry traders are therefore not compensated for bearing this risk.

The general consensus in the literature is that, while crash risk seems to account for a considerable portion of carry trade returns, it isn't possible to confirm that the excess returns to carry trades entirely reflect compensation for crash risk. In this paper, I further explore the crash risk hypothesis following Jurek's (2014) methodology over a longer period.

# 3. DATA

In this paper, I use data on the G10 currencies: the U.S. dollar (USD), the Australian dollar (AUD), British pound (GBP), the Canadian dollar (CAD), the euro (EUR), the Japanese yen (JPY), the New-Zealand dollar (NZD), the Norwegian krone (NOK), the Swedish krona (SEK), and the Swiss franc (CHF). Following Daniel et al. (2014), I also use the Deutsche Mark (DM) in place of the euro before its introduction in January 1999. The dataset includes the daily observations for spot and forward exchange rates for the nine G10 currencies against the USD obtained from DataStream. However, as presented in Section 4, I use the end-of-month observations to calculate the carry trade returns. I also use the one-month U.S. dollar London Interbank Offered Rate (LIBOR) obtained from Bloomberg. I derive the other currencies' short-term interest rates using the USD LIBOR, as well as the prevailing spot and forward exchange rates. The data span the period from January 1985 to May 2019.

I use foreign exchange options to build the hedged carry trade portfolios in Section 5. The foreign exchange option dataset includes daily price quotes in the form of implied volatilities obtained from J.P. Morgan DataQuery. However, as presented in Section 5, I use the end-of-month quotes to calculate the hedged carry trade returns. The implied volatility quotes are for one-month options on the G10 currencies at five delta levels: 10δ puts, 10δ calls, 25δ puts, 25δ calls, and 50δ options. The data span the period from January 1999 to August 2016.

Finally, in Section 6, I use data on S&P 500 index options obtained via OptionMetrics. These options are European and are AM-settled on the third Friday of every month. The dataset contains daily settlement prices on all the put and call options on the S&P 500 index, as well as the daily forward price of the underlying S&P 500 index. The data span the period from January 1999 to August 2016.

# 4. CURRENCY CARRY TRADES

In this paper, I take the perspective of a US-based investor. Currency *i* is the home currency, and currency *j* is the foreign currency. $S_t^{ji}$ represents the currency *i* price of purchasing one unit of currency *j*. Therefore, an increase (decrease) in $S_t^{ji}$ corresponds to an appreciation (depreciation) of the foreign currency relative to the USD. The short-term continuously compounded interest rates in markets *i* and *j* are $y_{t,t+\tau}^i$ and $y_{t,t+\tau}^j$, respectively.

To demonstrate the carry trade, consider an investor seeking to take advantage of the interest-rate differential between the domestic and foreign currencies. In this example, the domestic currency *i* (in this case, the USD) bears a lower interest rate and, therefore, is the funding currency. The foreign currency *j* bears a higher interest rate and, thus, is the investment currency. At time *t*, the trader borrows $S_t^{ji}$ dollars at the rate $y_{t,t+\tau}^i$. The borrowed dollars are converted to the foreign currency, and the investor lends them out for $\tau$ periods on market *j*, at the rate $y_{t,t+\tau}^j$. At time $t + \tau$, the carry trade is unwound; the proceeds from lending on market *j* are converted back to dollars and are used to cover the initial loan. In the case where the foreign currency bears a lower interest rate than the domestic one, their roles are simply reversed with the investor borrowing 1$ in foreign currency and investing it on the domestic market.

The excess returns to the carry trade are given by:

$$r_{t+\tau}^{ji} = \begin{cases} y_{t,t+\tau}^j > y_{t,t+\tau}^i : \exp\left(y_{t,t+\tau}^j \cdot \tau\right) \cdot \dfrac{S_{t+\tau}^{ji}}{S_t^{ji}} - \exp\left(y_{t,t+\tau}^i \cdot \tau\right) \\ y_{t,t+\tau}^i > y_{t,t+\tau}^j : \exp\left(y_{t,t+\tau}^i \cdot \tau\right) - \exp\left(y_{t,t+\tau}^j \cdot \tau\right) \cdot \dfrac{S_{t+\tau}^{ji}}{S_t^{ji}} \end{cases} \tag{1}$$

and are USD-denominated.

The returns to the carry trade are a combination of the interest rate differential, known as the carry, and the realized currency return. As the carry is known *ex-ante*, the carry trade's source of risk comes from the uncertainty regarding future exchange rates. Indeed, the carry trader is exposed to the risk of the sudden appreciation (depreciation) of the funding (investment) currency. Under UIP, the forward rate, $F^{ji}_{t,t+\tau} = S^{ji}_{t} \cdot \exp\left((y^{i}_{t,t+\tau} - y^{j}_{t,t+\tau}) \cdot \tau\right)$ provides an unbiased estimate of the future spot rate, $S^{ji}_{t,t+\tau}$, such that the expected excess return on the carry trade is zero.

### 4.1. Carry trade portfolios

Like Jurek (2014), rather than focus on individual currency pairs, I focus on portfolios of individual carry trades. At the end of month *t-1*, I establish positions in the nine G10 currencies depending on their interest rate differentials relative to the USD; I take a long (short) position in the currencies that have a positive (negative) interest rate differential. The positions are then held until the end of month *t*.

To determine the positions, I use the one-month USD LIBOR rate prevailing at the end of month *t-1*. I derive the foreign currency short-term rate using the prevailing spot and forward exchange rates, as well as the one-month USD LIBOR:

$$\exp\left(y^{j}_{t,t+\tau} \cdot \tau\right) = \frac{S^{ji}_{t}}{F^{ji}_{t,t+\tau}} \cdot \exp\left(y^{i}_{t,t+\tau} \cdot \tau\right) \tag{2}$$

I use two weighing schemes to weight the returns on the nine carry trades in the portfolio at each month *t*: spread- and equal-weighing. For the spread-weighted portfolio (SPR), the weights are determined by:

$$w^{SPR}_{j,t} = \frac{\left|y^{j}_{t,t+\tau} - y^{i}_{t,t+\tau}\right|}{\sum_{j=1}^{N_t}\left|y^{j}_{t,t+\tau} - y^{i}_{t,t+\tau}\right|} \tag{3}$$

where $N_t$ is the number of currencies at month *t*.

For the equal-weighted portfolio (EQL), the weights are determined by:

$$w^{EQL}_{j,t} = \frac{1}{N_t} \tag{4}$$

where $N_t$ is the number of currencies at month *t*.

I also establish dollar-neutral carry trade portfolios to determine whether the returns are affected by net dollar exposure. Indeed, Daniel et al. (2014) and Bekaert and Panayotov (2019) provide evidence that exposure to the US dollar has an effect on the returns to carry trades. Therefore, for both the spread- and equal-weighted portfolios, the weights are established to ensure that the net exposure to the dollar is zero. For the spread-weighted portfolio (SPR-$N), the weights are determined by:

$$w_{j,t}^{SPR-\$N} = \begin{cases} y_{t,t+\tau}^{j} > y_{t,t+\tau}^{i} : \dfrac{\left|y_{t,t+\tau}^{j} - y_{t,t+\tau}^{i}\right|}{\sum_{j=1}^{M_t}\left|y_{t,t+\tau}^{j} - y_{t,t+\tau}^{i}\right|} \\ y_{t,t+\tau}^{i} > y_{t,t+\tau}^{j} : \dfrac{\left|y_{t,t+\tau}^{j} - y_{t,t+\tau}^{i}\right|}{\sum_{j=1}^{O_t}\left|y_{t,t+\tau}^{j} - y_{t,t+\tau}^{i}\right|} \end{cases} \tag{5}$$

where $M_t$ ($O_t$) is the number of currencies which have a positive (negative) interest rate differential relative to the USD.

For the equal-weighted portfolio (EQL-$N), the weights are determined by:

$$w_{j,t}^{EQL-\$N} = \begin{cases} y_{t,t+\tau}^{j} > y_{t,t+\tau}^{i} : \dfrac{1}{M_t} \\ y_{t,t+\tau}^{i} > y_{t,t+\tau}^{j} : \dfrac{1}{O_t} \end{cases} \tag{6}$$

where $M_t$ ($O_t$) is the number of currencies which have a positive (negative) interest rate differential relative to the USD.

## 4.2. Historical performance

Table 1 presents the historical performance of the currency carry trade over the period extending from January 1985 to May 2019. Table 2 presents the analogous results over the period extending from January 1999 to August 2016, which corresponds to the span of the FX options data. As the exchange rates are expressed as the U.S. dollar price of purchasing one unit of foreign currency, the excess returns presented in the tables can be understood as U.S. dollar returns.

Panel A of both tables presents the historical performance of the currency carry trade at the individual currency level. Each strategy involves one of the G10 currencies and the U.S. dollar. Over the longer sample, the carry trade delivers positive mean excess returns for eight of the nine pairs. These mean excess returns are statistically significant in six cases. The annualized Sharpe ratio varies from -0.05 for the CHF/USD pair to 0.73 for the SEK/USD pair. In most cases, the returns to the carry trade are negatively skewed, indicating that the strategy is exposed to the risk of large losses. The results are slightly different over the shorter sample. Indeed, as is visible in Panel A of Table 2, only four pairs exhibit statistically significant excess returns, and four pairs exhibit positively skewed excess returns. Once again, the strategy exhibits the smallest annualized Sharpe ratio when it involves the CHF/USD pair and the largest when it involves the SEK/USD pair.

Panel B of both tables presents the summary statistics for the returns to portfolios of the individual currency carry trades. As explained earlier, the portfolios are either spread-weighted (SPR) or equal-weighted (EQL). Over the full sample, the average excess returns are positive and strongly statistically significant for both weighing schemes. In both cases, the mean return comes almost entirely from the interest rate carry component, leaving the rest to be accounted for by the realized currency return. The returns to both strategies demonstrate departures from normality, as they exhibit large negative skewness and significant kurtosis. Indeed, the maximum and minimum monthly returns are large in magnitude and fall approximately three standard deviations away from the (non-annualized) mean returns. The strategies also deliver higher Sharpe ratios than the Fama-French/Carhart equity market risk factors, as presented in Figure 1. For both the spread- and equal-weighted portfolios, the annualized standard deviation is lower than the average annualized volatility of the individual currency pairs, suggesting that the returns on the individual pairs are generally uncorrelated. The skewness, however, does not get diversified away, as the portfolio returns exhibit larger negative skewness than the individual pair returns. When comparing both portfolio strategies, the spread-weighted portfolio delivers higher average excess returns but also higher volatility than the equal-weighted portfolio, rendering their Sharpe ratios comparable. These features remain when looking at the results obtained over the shorter sample.

To examine whether the returns are affected by the exposure to the U.S. dollar, I also present the results for the dollar-neutral spread-weighted (SPR-$N) and equal-weighted (EQL-$N) portfolios in Panel B of Tables 1 and 2. As explained, these portfolios are constructed such that the exposure to the USD nets to zero. Over the full sample, the dollar-neutral portfolios exhibit positive, statistically significant mean excess returns as well as high, negative skewness and large kurtosis. Imposing the constraint of dollar-neutrality, however, reduces the average excess return by 2 and 20 basis points *per annum* for the equal- and spread-weighted strategies, respectively. This is visible in Figure 2, which plots the total return index for the spread-weighted portfolio when it is and isn't constrained to be dollar-neutral. These features remain when looking at the results over the shorter sample, although the mean returns to the EQL-$N portfolio are not statistically significant. The return differential between non-dollar-neutral and dollar-neutral portfolios can be explained by the fact that both the spread- and equal-weighted portfolios exhibited negative average net exposure to the USD over the period studied, as is visible in Figure 3. Table 3 presents the summary statistics for the returns to shorting the USD against an equal-weighted basket of the remaining G10 currencies. These returns are positive on average, implying that the USD tended to act as a funding currency throughout both the full and short samples and that negative exposure to the USD contributed positively to the portfolio returns.

Overall, the historical performance of the carry trade demonstrates that the strategy generates large, positive excess returns, which are exposed to the risk of large currency crashes, as evidenced by their high, negative skewness. This observation is at the basis of Section 5, in which I explore whether the excess returns to the carry trade can be understood as being compensation for the exposure to crash risk.

**Table 1 - Currency Carry Trades (1985:1 - 2019:5)**

The table reports summary statistics for the period extending from January 1985 to May 2019 ($N$ = 413 months). The returns are computed monthly. The means, standard deviations, and Sharpe Ratios are annualized. *Carry* reports the mean absolute interest rate differential, $|y^j_{t,t+\tau}$, - $y^i_{t,t+\tau}|$. *Minimum* and *Maximum* report the smallest and largest observed monthly return. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors of the mean estimates are HAC robust. Panel A presents the summary statistics for the returns to the carry trade involving the USD and one of the nine remaining G10 currencies. Panel B presents the summary statistics for the returns to the different carry trade portfolios. The allocations to individual currencies are either spread-weighted (SPR) or equal-weighted (EQL) and can also be required to be dollar-neutral ($N).

**Panel A: Individual Currencies**

| | JPY | CHF | EUR | SEK | CAD | GBP | NOK | AUD | NZD |
|---|---|---|---|---|---|---|---|---|---|
| **Mean** | 0.0205<br>[1.08] | -0.0060<br>[-0.31] | 0.0407 *<br>[1.88] | 0.0796 ***<br>[4.31] | 0.0001<br>[0.01] | 0.0327 *<br>[1.91] | 0.0409 **<br>[2.22] | 0.0558 ***<br>[2.81] | 0.0686 ***<br>[3.28] |
| **Std. Dev** | 0.1107 | 0.1137 | 0.0976 | 0.1084 | 0.0737 | 0.1006 | 0.1080 | 0.1163 | 0.1225 |
| **Skewness** | -0.57 | -0.38 | 0.1 | -0.31 | -0.22 | 0.01 | -0.45 | -0.70 | -0.19 |
| **Kurtosis** | 5.18 | 3.79 | 4.41 | 4.1 | 6.57 | 5.34 | 3.84 | 5.61 | 4.65 |
| **Minimum** | -0.1690 | -0.1345 | -0.0795 | -0.1441 | -0.0939 | -0.1192 | -0.1206 | -0.1792 | -0.1256 |
| **Maximum** | 0.1021 | 0.1116 | 0.1153 | 0.1045 | 0.119 | 0.1409 | 0.076 | 0.0957 | 0.1329 |
| **Carry** | 0.0276 | 0.0239 | 0.0094 | 0.0287 | 0.0123 | 0.01835 | 0.0325 | 0.0353 | 0.0448 |
| **SR** | 0.18 | -0.05 | 0.42 | 0.73 | 0 | 0.32 | 0.38 | 0.48 | 0.56 |

**Panel B: Portfolio Strategies**

| | SPR | SPR-$N | EQL | EQL-$N |
|---|---|---|---|---|
| **Mean** | 0.0598 ***<br>[4.70] | 0.0578 ***<br>[3.63] | 0.0343 ***<br>[4.09] | 0.0345 ***<br>[2.78] |
| **Std. Dev** | 0.0746 | 0.0936 | 0.0492 | 0.0728 |
| **Skewness** | -0.40 | -0.69 | -0.67 | -0.60 |
| **Kurtosis** | 4.42 | 4.34 | 4.34 | 4.11 |
| **Minimum** | -0.0694 | -0.1021 | -0.0521 | -0.0810 |
| **Maximum** | 0.0742 | 0.0812 | 0.0435 | 0.0528 |
| **Carry** | 0.0436 | 0.0676 | 0.0267 | 0.0467 |
| **SR** | 0.80 | 0.62 | 0.70 | 0.47 |

**Table 2 - Currency Carry Trades (1999:1 – 2016:8)**

The table reports summary statistics for the period extending from January 1999 to August 2016 ($N$ = 212 months). The returns are computed monthly. The means, standard deviations, and Sharpe Ratios are annualized. *Carry* reports the mean absolute interest rate differential, $|y^{j}_{t,t+\tau}$, - $y^{i}_{t,t+\tau}|$. *Minimum* and *Maximum* report the smallest and largest observed monthly return. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors of the mean estimates are HAC robust. Panel A presents the summary statistics for the returns to the carry trade involving the USD and one of the nine remaining G10 currencies. Panel B presents the summary statistics for the returns to the different carry trade portfolios. The allocations to individual currencies are either spread-weighted (SPR) or equal-weighted (EQL) and can also be required to be dollar-neutral ($N).

**Panel A: Individual Currencies**

| | JPY | CHF | EUR | SEK | CAD | GBP | NOK | AUD | NZD |
|---|---|---|---|---|---|---|---|---|---|
| **Mean** | 0.0108<br>[0.47] | -0.0086<br>[-0.33] | 0.0457 *<br>[1.88] | 0.0764 ***<br>[2.88] | -0.0315<br>[-1.47] | 0.0014<br>[0.07] | 0.0080<br>[0.30] | 0.0508 *<br>[1.67] | 0.0776 **<br>[2.42] |
| **Std. Dev** | 0.0959 | 0.1085 | 0.1020 | 0.1114 | 0.0899 | 0.0883 | 0.1119 | 0.1277 | 0.1343 |
| **Skewness** | 0.08 | -0.38 | 0.08 | 0.08 | 0.02 | -0.12 | -0.30 | -0.64 | -0.41 |
| **Kurtosis** | 3.09 | 4.66 | 4.22 | 3.24 | 5.43 | 4.62 | 3.58 | 5.49 | 4.29 |
| **Minimum** | -0.0727 | -0.1345 | -0.0795 | -0.0724 | -0.0939 | -0.0995 | -0.1206 | -0.1792 | -0.1256 |
| **Maximum** | 0.0825 | 0.1116 | 0.1153 | 0.1045 | 0.1189 | 0.0917 | 0.0719 | 0.0957 | 0.1328 |
| **Carry** | 0.022 | 0.0152 | 0.0092 | 0.0146 | 0.0071 | 0.009 | 0.01838 | 0.0253 | 0.0288 |
| **SR** | 0.11 | -0.08 | 0.45 | 0.69 | -0.35 | 0.02 | 0.07 | 0.4 | 0.58 |

**Panel B: Portfolio Strategies**

| | SPR | SPR-$N | EQL | EQL-$N |
|---|---|---|---|---|
| **Mean** | 0.0458 **<br>[2.39] | 0.0442 **<br>[2.03] | 0.0256 **<br>[2.18] | 0.0247<br>[1.56] |
| **Std. Dev** | 0.0805 | 0.0914 | 0.0492 | 0.0664 |
| **Skewness** | -0.25 | -0.57 | -0.35 | -0.40 |
| **Kurtosis** | 4.45 | 4.63 | 3.77 | 3.92 |
| **Minimum** | -0.0694 | -0.1021 | -0.0431 | -0.0632 |
| **Maximum** | 0.0742 | 0.0812 | 0.0435 | 0.0527 |
| **Carry** | 0.0281 | 0.0423 | 0.0166 | 0.0288 |
| **SR** | 0.57 | 0.48 | 0.52 | 0.37 |

**Table 3 - Shorting the U.S. Dollar**

The table reports summary statistics for the returns to shorting the U.S. dollar against an equal-weighted basket of the nine G10 currencies for the period extending from January 1985 to May 2019 ($N$ = 413 months), as well as for the period extending from January 1999 to August 2012 ($N$ = 211 months). The means, standard deviations, and Sharpe Ratios are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors of the mean estimates are HAC robust.

| | **1985:1 – 2019:5** | **1999:1 – 2016:8** |
|---|---|---|
| **Mean** | 0.0224<br>[1.65] | 0.0140<br>[0.69] |
| **Std. Dev** | 0.0800 | 0.0841 |
| **Skewness** | -0.08 | -0.13 |
| **Kurtosis** | 3.78 | 3.98 |
| **SR** | 0.28 | 0.17 |

**Figure 1 - Total Return Indices**

This figure depicts the total return indices for the three Fama-French factors, the momentum factor, as well as the spread-weighted carry trade portfolio (SPR) over the period extending from January 1985 to May 2019 (*N* = 413 months). The carry trade portfolio is composed of individual carry trades involving the USD and each of the remaining G10 currencies and is re-balanced monthly. The factors' monthly excess returns are compounded and scaled ex-post to match the volatility of the carry trade returns.
The table reports summary statistics for the returns to each strategy. The Fama-French factors are from Kenneth French's data library. The means, standard deviations, and Sharpe Ratios are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors of the mean estimates are HAC robust.

| | **RMRF** | **SMB** | **HML** | **UMD** | **Carry Trade (SPR)** |
|---|---|---|---|---|---|
| **Mean** | 0.0836 *** | 0.0041 | 0.0195 | 0.0642 ** | 0.0598 *** |
| | [3.23] | [0.23] | [1.15] | [2.40] | [4.70] |
| **Std. Dev** | 0.1518 | 0.1064 | 0.0994 | 0.1566 | 0.0746 |
| **Skewness** | -0.90 | 0.63 | 0.32 | -1.52 | -0.40 |
| **SR** | 0.55 | 0.04 | 0.20 | 0.41 | 0.80 |

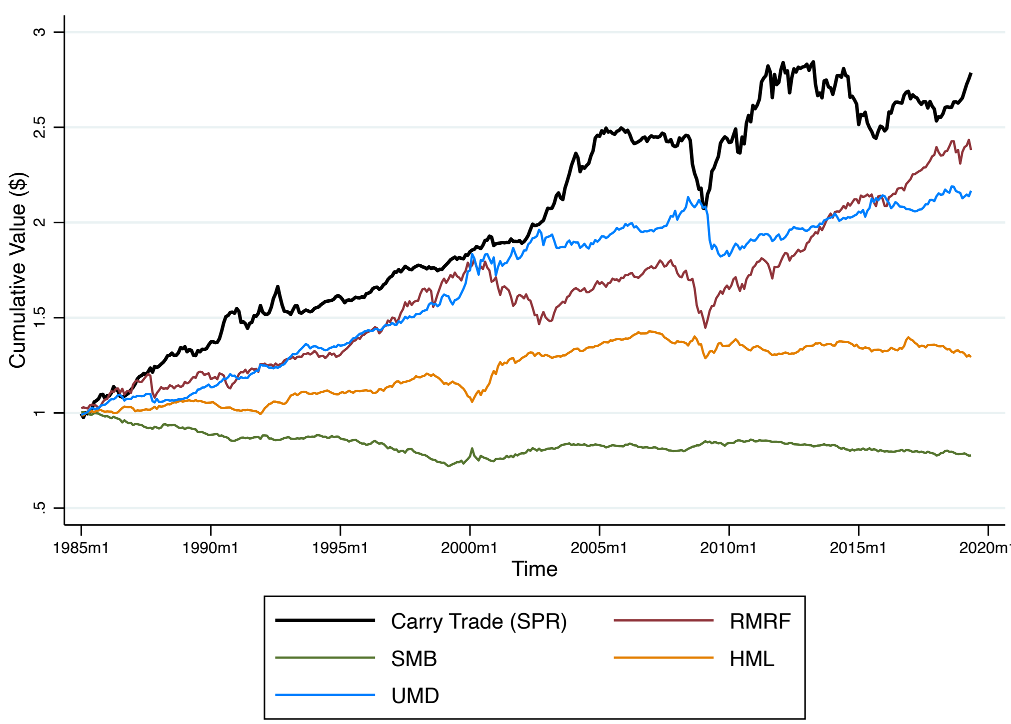


**Figure 2 - Cumulative Returns to the SPR and SPR-$N Portfolios**

This figure depicts the total return indices for the spread-weighted (SPR) and dollar-neutral spread-weighted (SPR-$N) portfolios over the period extending from January 1985 to May 2019 ($N$ = 413 months). The portfolios are composed of individual carry trades involving the USD and each of the remaining G10 currencies and are re-balanced monthly.

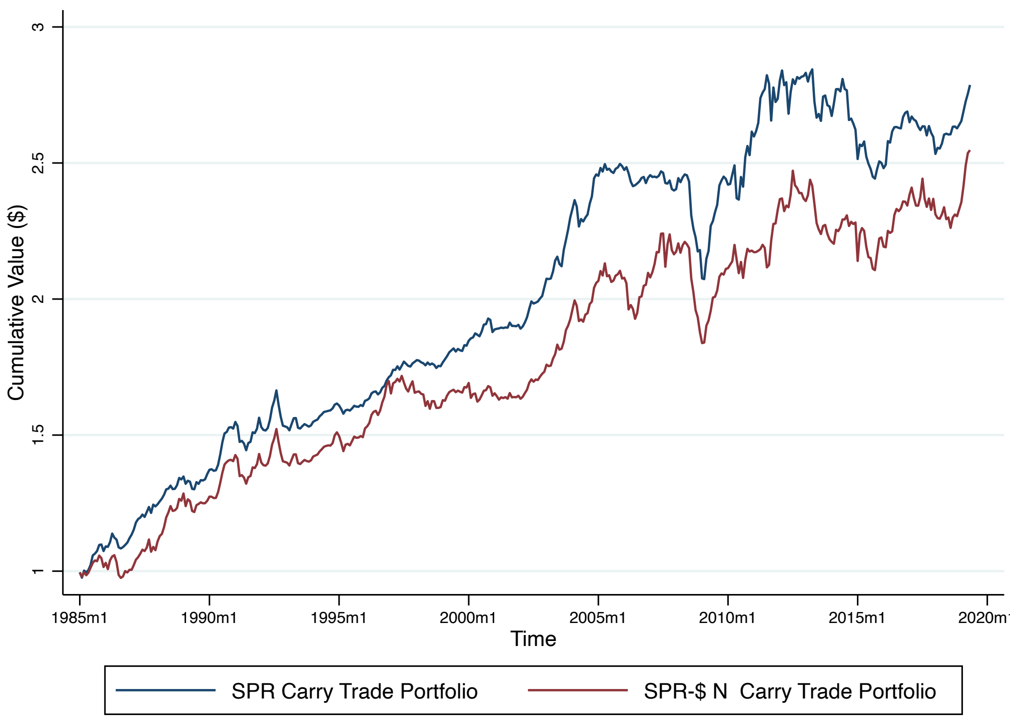
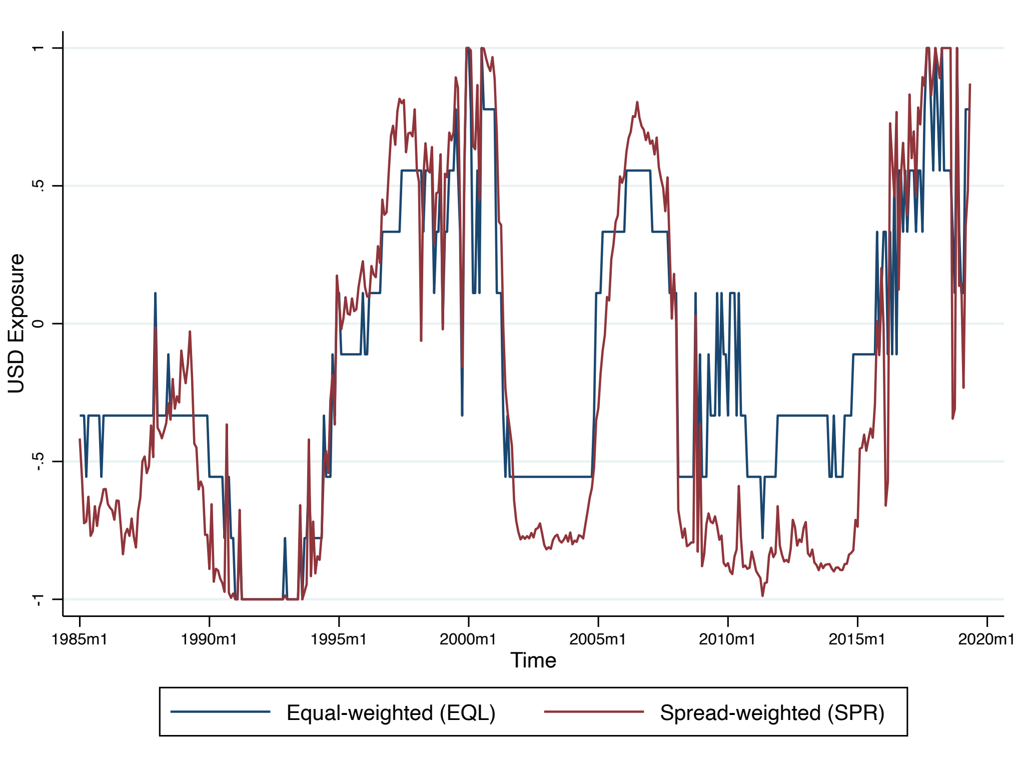


**Figure 3 - U.S. Dollar Exposure**

This figure depicts the net dollar exposure for the equal-weighted (EQL) and spread-weighted (SPR) carry trade portfolios over the period extending from January 1985 to May 2019 ($N$ = 413 months). The portfolios are composed of individual carry trades involving the USD and each of the remaining G10 currencies and are re-balanced monthly. A negative (positive) exposure to the USD indicates the portfolio was net short (long) the currency.



# 5. CRASH-NEUTRAL CURRENCY CARRY TRADES

Given the high negative skewness of carry trade returns demonstrated in Section 4, I build crash-neutral carry trades in order to examine the crash risk hypothesis. Like Jurek (2014), I use foreign exchange options to eliminate the trades' exposure to rapid depreciations (appreciations) of the investment (funding) currencies. Specifically, when the carry trade involves a long position in the foreign currency, the strategy includes purchasing put options on the $S_t^{ji}$ exchange rate to limit the risk of a sudden depreciation of said currency. When it involves a short position in the foreign currency, the strategy includes purchasing call options on the exchange rate to eliminate the risk of the sudden appreciation of the currency. Following Jurek (2014), the crash-neutral carry trades are built to:

(1) Ensure that all currency risk exposure is eliminated, conditional on the options expiring in-the-money;

(2) Ensure that the *ex-ante* currency exposure of both the standard and crash-hedged carry trades is identical by hedging the option overlay.

The second condition ensures that the returns to the unhedged and hedged carry trade portfolios are directly comparable. Intuitively, the excess returns to the unhedged carry trade can be entirely attributed to a crash risk premium if the returns to the hedged carry trade are statistically indistinguishable from zero.

## 5.1. Crash-neutral carry trade portfolios

To construct the crash-neutral carry trade portfolio, I use the same method as presented in Section 4 for the standard carry trade portfolio. At the end of each month, I take positions in each of the nine G10 currencies against the USD on the basis of their prevailing short-term interest rate. I combine each carry trade with a position in the appropriate one-month FX options. The positions are held until the end of the following month. Like the standard carry trade portfolio construction, I build spread- and equal-weighted hedged carry trade portfolios, as well as the dollar-neutral variants. Following, I present the crash-neutral carry trade return calculation for the two possible scenarios: a positive and a negative interest rate differential.

### *5.1.1 The foreign currency is the investment currency*

If the foreign interest rate exceeds the domestic rate, the carry trade is established with a long position in the foreign currency. The trader is therefore exposed to the risk of a sudden depreciation of the foreign currency and seeks to hedge this exposure through the purchase of $q_p$ put options on the exchange rate. The purchase of said options is funded by borrowing in the domestic currency. To hedge the options' negative delta exposure, the trader must also purchase $-q_p \cdot \delta_p$ units of the foreign currency and fund this purchase by borrowing an additional $q_p \cdot \delta_p \cdot S_t$ units of the domestic currency. At time *t+1*, the payoff to the hedged carry trade strategy is:

$$\tilde{c}^{ji}_{t+\tau} = \exp\left(y^{j}_{t,t+\tau} \cdot \tau\right) \cdot \left(1 - q_p \cdot \delta_p\right) \cdot S^{ji}_{t+\tau} + q_p \cdot \max\left(K_p - S^{ji}_{t+\tau}, 0\right) - \exp\left(y^{i}_{t,t+\tau} \cdot \tau\right) \cdot \left(\left(1 - q_p \cdot \delta_p\right) \cdot S^{ji}_{t} + q_p \cdot P_t\left(K_p, \tau\right)\right) \quad (7)$$

where $K_p$ and $P_t(K_p, \tau)$ represent the option strike price and premium respectively.

The return to the strategy is:

$$\tilde{r}^{ji}_{t+\tau} = \exp\left(y^{j}_{t,t+\tau} \cdot \tau\right) \cdot \left(1 - q_p \cdot \delta_p\right) \cdot \frac{S^{ji}_{t+\tau}}{S^{ji}_{t}} + q_p \cdot \max\left(\frac{K_p}{S^{ji}_{t}} - \frac{S^{ji}_{t+\tau}}{S^{ji}_{t}}, 0\right) - \exp\left(y^{i}_{t,t+\tau} \cdot \tau\right) \cdot \left(\left(1 - q_p \cdot \delta_p\right) + q_p \cdot \frac{P_t\left(K_p, \tau\right)}{S^{ji}_{t}}\right) \quad (8)$$

In order to ensure that below the strike price, all currency risk exposure is eliminated, the quantity of puts purchased must respect:

$$q_p = \exp\left(y^{j}_{t,t+\tau} \cdot \tau\right) \cdot \left(1 - q_p \cdot \delta_p\right) \rightarrow \ q_p = \frac{\exp\left(y^{j}_{t,t+\tau} \cdot \tau\right)}{1 + \exp\left(y^{j}_{t,t+\tau} \cdot \tau\right) \cdot \delta_p} \quad (9)$$

The return to the strategy can therefore be re-written as:

$$\tilde{r}^{ji}_{t+\tau} = q_p \cdot \max\left(\frac{K_p}{S^{ji}_{t}}, \frac{S^{ji}_{t+\tau}}{S^{ji}_{t}}\right) - \exp\left(y^{i}_{t,t+\tau} \cdot \tau\right) \cdot \left(\left(1 - q_p \cdot \delta_p\right) + q_p \cdot \frac{P_t\left(K_p, \tau\right)}{S^{ji}_{t}}\right) \quad (10)$$

The carry trader is no longer exposed to depreciations of the foreign currency below the strike price of the option, $K_p$. However, the trader's exposure to appreciations of the foreign currency is increased. Indeed, for values of $S^{ji}_{t+\tau}$ that are above the strike, the returns to the hedged strategy are more sensitive to changes in the exchange rate than they are in the case of the unhedged strategy, as the quantity $q_p$ is strictly greater than the foreign rate $y^{j}_{t,t+\tau} \cdot \tau$, since $\delta_p$ is negative (equation 9). Thus, the option overlay $(-q_p \cdot \delta_p)$ locally hedges away the option-induced exposure of the position to the exchange rate. However, this exposure will vary between the inception of the trade and the settlement 30 days later.

### *5.1.2 The foreign currency is the funding currency*

If the domestic interest rate exceeds the foreign rate, the carry trade is established with a short position in the foreign currency. The trader is therefore exposed to the risk of a sudden appreciation of the foreign currency and seeks to hedge this exposure through the purchase of $q_c$ call options on the exchange rate. The purchase of said options is funded by borrowing the funds at the domestic interest rate. To hedge the options' positive delta exposure, the trader must also short $q_c \cdot \delta_c$ units of the foreign currency. At time *t+1*, the payoff to the hedged carry trade strategy is:

$$\tilde{c}_{t+\tau}^{ji} = \exp\left(y_{t,t+\tau}^{i} \cdot \tau\right) \cdot \left((1 + q_c \cdot \delta_c) \cdot S_t^{ji} - q_c \cdot C_t(K_c, \tau)\right) + q_c \cdot \max\left(S_{t+\tau}^{ji} - K_c, 0\right) - \exp\left(y_{t,t+\tau}^{j} \cdot \tau\right) \cdot (1 + q_c \cdot \delta_c) \cdot S_{t+\tau}^{ji} \quad (11)$$

where $K_c$ and $C_t(K_c, \tau)$ represent the option strike price and premium respectively.

The return to the strategy is:

$$\tilde{c}_{t+\tau}^{ji} = \exp\left(y_{t,t+\tau}^{i} \cdot \tau\right) \cdot \left((1 + q_c \cdot \delta_c) - q_c \cdot \frac{C_t(K_c, \tau)}{S_t^{ji}}\right) + q_c \cdot \max\left(\frac{S_{t+\tau}^{ji}}{S_t^{ji}} - \frac{K_c}{S_t^{ji}}, 0\right) - \exp\left(y_{t,t+\tau}^{j} \cdot \tau\right) \cdot (1 + q_c \cdot \delta_c) \cdot \frac{S_{t+\tau}^{ji}}{S_t^{ji}} \quad (12)$$

In order to ensure that above the strike price, all currency risk exposure is eliminated, the quantity of calls purchased must respect:

$$q_c = \exp\left(y_{t,t+\tau}^{j} \cdot \tau\right) \cdot (1 + q_c \cdot \delta_c) \rightarrow \; q_c = \frac{\exp\left(y_{t,t+\tau}^{j} \cdot \tau\right)}{1 - \exp\left(y_{t,t+\tau}^{j} \cdot \tau\right) \cdot \delta_c} \quad (13)$$

The return to the strategy can therefore be re-written as:

$$\tilde{r}_{t+\tau}^{ji} = \exp\left(y_{t,t+\tau}^{i} \cdot \tau\right) \cdot \left((1 + q_c \cdot \delta_c) - q_c \cdot \frac{C_t(K_c, \tau)}{S_t^{ji}}\right) - q_c \cdot \min\left(\frac{K_c}{S_t^{ji}}, \frac{S_{t+\tau}^{ji}}{S_t^{ji}}\right) \quad (14)$$

The carry trader is no longer exposed to appreciations of the foreign currency above the strike price $K_c$. However, the trader's exposure to depreciations of the foreign currency is increased. Indeed, for values of $S_{t+\tau}^{ji}$ that are below the strike, the returns to the hedged strategy are more sensitive to changes in the exchange rate than they are in the case of the unhedged strategy, as the quantity $q_c$ is strictly greater than the foreign rate $y_{t,t+\tau}^{j} \cdot \tau$ (equation 13). Once again, the option overlay ($q_c \cdot \delta_c$) locally hedges away the option-induced exposure of the position to the exchange rate. However, between the inception of the trade and the settlement 30 days later, this exposure will vary over time.

## 5.2. Foreign exchange options

Here, I provide information on the formulas used to calculate the FX option strike prices and premiums. Once again, I follow the methods used by Jurek (2014) [4].

Starting with one-month FX option implied volatility quotes for $10\delta$, $25\delta$, and at-the-money call and put options, I use the following formulas to calculate the option strikes:

$$K_{\delta_c} = F_{t,t+\tau}^{ji} \cdot \exp\left(\frac{1}{2} \cdot \sigma_t(\delta_c)^2 \cdot \tau - \sigma_t(\delta_c) \cdot \sqrt{\tau} \cdot N^{-1}\left[exp\left(y_{t,t+\tau}^{j}\right) \cdot \delta_c\right]\right) \qquad (15.a)$$

$$K_{\delta_p} = F_{t,t+\tau}^{ji} \cdot \exp\left(\frac{1}{2} \cdot \sigma_t\left(\delta_p\right)^2 \cdot \tau + \sigma_t\left(\delta_p\right) \cdot \sqrt{\tau} \cdot N^{-1}\left[-exp\left(y_{t,t+\tau}^{j}\right) \cdot \delta_p\right]\right) \qquad (15.b)$$

$$K_{ATM} = F_{t,t+\tau}^{ji} \cdot \exp\left(\frac{1}{2} \cdot \sigma_t(ATM)^2 \cdot \tau\right) \qquad (15.c)$$

where $\sigma_t(\delta)$ is the option's implied volatility quote, for a given delta.

To then calculate both the call and put FX option prices, I use the Garman-Kohlhagen (1983) valuation formulas:

$$C_t\left(S_t^{ji}, K, \tau, y_{t,t+\tau}^{i}, y_{t,t+\tau}^{j}\right) = \exp\left(-y_{t,t+\tau}^{i}\right) \cdot \left[F_{t,\tau} \cdot N(d_1) - K \cdot N(d_2)\right] \qquad (16.a)$$

$$P_t\left(S_t^{ji}, K, \tau, y_{t,t+\tau}^{i}, y_{t,t+\tau}^{j}\right) = \exp\left(-y_{t,t+\tau}^{i}\right) \cdot \left[K \cdot N(-d_2) - F_{t,\tau} \cdot N(-d_1)\right] \qquad (16.b)$$

where

$$d_1 = \frac{\ln\left(F_{t,t+\tau}^{ji}/K\right)}{\sigma_t(K,\tau) \cdot \sqrt{\tau}} + \frac{1}{2} \cdot \sigma_t(K,\tau) \cdot \sqrt{\tau} \qquad (17)$$

$$d_2 = d_1 - \sigma_t(K,\tau) \cdot \sqrt{\tau}$$

## 5.3. Crash risk premium

Jurek (2014) decomposes the risk premium of currency exposure into a risk premium for the exposure to diffusive shocks ($\lambda^d$) and a risk premium for the exposure to jump shocks ($\lambda^j$). Jump shocks correspond to large currency moves, which have an extreme negative

[4] The option deltas are obtained by differentiating the option price equations with respect to the spot exchange rate, $S_t^{ji}$. The option strike price equations are derived from the option delta equations. See Jurek (2014) for the detailed derivations.

impact on the carry trade returns; they contribute mass to the far-left tail of the return distribution. He demonstrates that conditional on the absence of *peso problems* in the data, the average returns to the unhedged carry trade portfolio approximately correspond to the sum of both premia ($\lambda^u = \lambda^d + \lambda^j$), and the average excess returns to the crash hedged carry trade portfolio provide an estimate of the diffusive risk premium ($\lambda^d$). Therefore, subtracting the mean excess returns to the crash-neutral carry trade portfolio from the mean returns to the standard carry trade portfolio provides an estimate of the jump risk premium ($\lambda^j$).

### 5.4. Results

Table 4 presents the summary statistics for the returns to the crash-hedged carry trade portfolios. As in Section 4, I report the results for non- and dollar-neutral portfolios.

As expected, when compared to the unhedged portfolios, the returns to the hedged portfolios exhibit more positive skewness. This is illustrated in Figure 4. Indeed, in the figure, the spread-weighted unhedged portfolio returns exhibit significant deviations from the normal distribution on the left tail. This is gradually eliminated as hedging becomes more aggressive. The smallest realized monthly return also increases by approximately 6% for the spread-weighted portfolio and 20% for the equal-weighted one, when comparing the unhedged and $10\delta$-hedged portfolios. For both weighing schemes, the average returns to the hedged portfolio remain positive and statistically significant in 5 of the 6 cases. However, the realized returns decrease as hedging becomes more aggressive, as is illustrated in Figure 5. Although the mean returns to the hedged portfolios gradually decrease, so do their standard deviations, resulting in the Sharpe Ratio remaining at a similar level to that of the unhedged portfolio, for both weighing schemes.

As explained earlier, the crash risk premium can be understood as being the difference between the average returns to the unhedged and hedged portfolio, conditional on the absence of *peso problems* in the data. The positive and, for the most part, statistically significant average returns to the hedged portfolios are indicative of the absence of a *peso problem* and thus of the accuracy of the jump risk premium estimation. The results reveal a small crash risk premium ranging between 0.15% ($10\delta$; t-stat: 0.37) and 2.45% (ATM; t-stat: 2.07) when looking at the spread-weighted portfolios. When looked at as a portion of the unhedged portfolio returns, the crash risk premium accounts for 3.28% to 53.49% of the total risk premium. The declines in excess returns are larger in magnitude for the equal-weighted portfolios, and the crash risk premium accounts for 9.77% to 63.67% of the total risk premium.

Panel B reports the same summary statistics, this time when looking at portfolios that have been constrained to be dollar neutral. As presented in Section 4, this constraint lowers the average portfolio returns. It is therefore expected that although the hedged dollar-neutral portfolios' realized returns remain positive, they are statistically significant in 2 of the 6 cases. Once again, the skewness becomes more positive as hedging becomes more aggressive. The crash risk premium ranges from 0.33% ($10\delta$; t-stat: 0.52) to 3.05% (ATM; t-stat: 1.77) and accounts for 7.47% to 69.00% of the total risk premium when looking at the spread-weighted portfolios. Once again, the crash risk premium is larger and accounts for a larger portion of the total risk premium when looking at the equal-weighted portfolios.

Overall, while the hedged portfolios' average excess returns remain positive and, in some cases, statistically significant, providing evidence against the crash-risk hypothesis, they are smaller in magnitude, indicating that the unhedged trade earns a crash risk premium. Following Jurek's (2014) approach, I focus on the results obtained for the 10$\delta$-hedged portfolios. Indeed, at-the-money options hedge the carry trade against all currency moves having a negative effect on the strategy's payoffs. Since the aim is to eliminate the carry trade's exposure to extreme currency moves, the results obtained when using the most deep out-of-the-money options are more pertinent and provide the most accurate measure of the crash risk premium. With this in mind, the crash risk premium estimations are small and explain at most 18.62% (10$\delta$-hedged, EQL-$N) of the excess returns to the standard carry trade. The high returns to the carry trade can therefore not be rationalized as solely being compensation for bearing currency crash risk.

My findings contrast with Jurek's (2014). He finds that the crash risk premium accounts for at most one third of the total currency risk premium, whereas I find that it accounts for at most 18.62%. This could be because my dataset covers a longer period; his data span the period from January 1999 to June 2012, whereas mine ends in August 2016.

*5.4.1. The 2008 financial crisis*

As mentioned, Figure 5 illustrates the total return indices for the unhedged and hedged carry trade portfolios. The returns to these portfolios all experience significant losses around the end of 2008. Indeed, during this period, the unhedged carry trade had negative net exposure to the USD (Figure 3), all while the USD appreciated against most of the G10 currencies (Figure 6). Furthermore, the JPY appreciated against the USD during this time, while all the portfolios were short the currency. Brunnermeier et al. (2008) provide insight on the mechanics behind the carry trade losses. They document a significant link between currency crashes and increases in stock market volatility. Indeed, they find than an increase in the VIX equity option implied volatility index coincides with the unwinding of carry trades. This suggests that as the VIX increased during the fall of 2008, following the onset of the credit crisis, speculators' risk tolerance declined, causing them to reduce their carry trade positions. This then caused the depreciation of investment currencies and the appreciation of funding currencies, and consequently, carry trade losses.

While these factors can explain the standard carry trade portfolio losses, one would expect that the hedged portfolios are protected against such an event. However, when taking a closer look at the monthly returns during this period, it is possible to describe the decline in 2008 as a succession of losses rather than a single crash (Table 5). Indeed, when compared with the historical realized monthly volatility for the January 1999 – August 2016 period, the returns to the spread-weighted portfolio represent -2.45, -1.95, and -2.25 standard deviation moves in August, September, and October of 2008, respectively. These negative returns cannot be qualified as being extreme losses, given the large kurtosis of the portfolio's return distribution. During this same period, the 10$\delta$-hedged (25$\delta$-hedged) spread-weighted portfolio also earns negative returns, although these losses are less important and represent on average -1.68 (-1.07) standard deviation moves per month in August, September, and October of 2008. The fall of 2008 is also marked by the gradual increase of the foreign exchange option implied volatilities. The progressive rise in implied volatility meant that the options became gradually more out-of-the-money, increasingly exposing the carry trade portfolios to more potential losses. This suggests fixed-delta options do not adequately hedge against gradual and prolonged declines, such as the 2008 crisis. Jurek (2014) presents the results when constructing crash-neutral carry trades that are hedged using options with a fixed moneyness. This hedging scheme ensures that the losses are capped but is more costly as it requires purchasing options that are relatively more at-the-money in times when the option implied volatilities are rising, such as in the fall of 2008. He finds that the increased protection provided by fixed moneyness hedging is offset by the higher cost of the strategy, and the returns to both fixed delta and fixed moneyness hedging are statistically indistinguishable.

Given the evidence that the carry trade seems to be exposed to crashes in the stock market, it is natural to ask whether exposure to tail events in the equity market an explain the excess returns to carry trades. This is what I explore in the following section.

**Table 4 - Crash-Neutral Currency Carry Trades (1999:1 – 2016:8)**

The table reports summary statistics for the period extending from January 1999 to August 2016 ($N$ = 212 months). The returns are computed monthly. The allocations to individual currencies are either spread-weighted (SPR) or equal-weighted (EQL). The means, standard deviations, and Sharpe Ratios are annualized. *Minimum* and *Maximum* report the smallest and largest observed monthly return. *Difference* reports the difference between the mean returns to the unhedged portfolio and the returns to the hedged portfolio. *Share* reports the portion of the unhedged carry trade returns that can be attributed to the jump risk premium; it is computed by taking the difference between the mean returns to the unhedged and hedged portfolios and dividing it by the returns to the unhedged portfolio. Panel A reports summary statistics for portfolios not required to be dollar-neutral. Panel B reports summary statistics for portfolios required to be dollar-neutral ($N). The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors of the mean estimates are HAC robust.

**Panel A: Non-Dollar-Neutral Portfolio Returns**

| | Unhedged | | 10$\delta$-hedged | | 25$\delta$-hedged | | ATM-hedged | |
|---|---|---|---|---|---|---|---|---|
| | SPR | EQL | SPR | EQL | SPR | EQL | SPR | EQL |
| **Mean** | 0.0458 ** | 0.0256 ** | 0.0443 *** | 0.0231 ** | 0.0370 ** | 0.0182 * | 0.0213 * | 0.0093 |
| | [2.39] | [2.18] | [2.60] | [2.18] | [2.48] | [1.90] | [1.88] | [1.23] |
| **Std. Dev** | 0.0805 | 0.0492 | 0.0714 | 0.0444 | 0.0624 | 0.0402 | 0.0473 | 0.0318 |
| **Skewness** | -0.25 | -0.35 | 0.26 | 0.04 | 0.68 | 0.28 | 1.34 | 0.84 |
| **Kurtosis** | 4.45 | 3.77 | 4.10 | 3.50 | 4.39 | 3.87 | 5.45 | 4.14 |
| **Minimum** | -0.0694 | -0.0431 | -0.0650 | -0.0343 | -0.0521 | -0.0406 | -0.0340 | -0.0273 |
| **Maximum** | 0.0742 | 0.0435 | 0.0706 | 0.0404 | 0.066 | 0.035 | 0.0558 | 0.0318 |
| **SR** | 0.57 | 0.52 | 0.62 | 0.52 | 0.59 | 0.45 | 0.45 | 0.29 |
| **Difference** | - | - | 0.0015 | 0.0025 | 0.0088 | 0.0074 | 0.0245 ** | 0.0163 * |
| | - | - | [0.37] | [0.85] | [1.13] | [1.31] | [2.07] | [1.95] |
| **Share** | | | 3.28% | 9.77% | 19.21% | 28.91% | 53.49% | 63.67% |

**Panel B: Dollar-Neutral Portfolio Returns**

| | Unhedged | | 10$\delta$-hedged | | 25$\delta$-hedged | | ATM-hedged | |
|---|---|---|---|---|---|---|---|---|
| | SPR-$N | EQL-$N | SPR-$N | EQL-$N | SPR-$N | EQL-$N | SPR-$N | EQL-$N |
| **Mean** | 0.0442 ** | 0.0247 | 0.0409 ** | 0.0201 | 0.0319 * | 0.0141 | 0.0137 | 0.0023 |
| | [2.03] | [1.56] | [2.12] | [1.41] | [1.84] | [1.05] | [0.94] | [0.20] |
| **Std. Dev** | 0.0914 | 0.0664 | 0.0808 | 0.0597 | 0.0726 | 0.0561 | 0.061 | 0.0495 |
| **Skewness** | -0.57 | -0.4 | -0.10 | -0.06 | 0.08 | -0.11 | 0.6 | 0.36 |
| **Kurtosis** | 4.63 | 3.92 | 3.52 | 3.19 | 3.63 | 3.10 | 3.50 | 2.95 |
| **Minimum** | -0.1021 | -0.0632 | -0.0658 | -0.0490 | -0.0719 | -0.0542 | -0.0529 | -0.0402 |
| **Maximum** | 0.08122 | 0.0527 | 0.0752 | 0.0487 | 0.0634 | 0.0408 | 0.0572 | 0.0406 |
| **SR** | 0.48 | 0.37 | 0.51 | 0.37 | 0.44 | 0.25 | 0.23 | 0.47 |
| **Difference** | - | - | 0.0033 | 0.0046 | 0.0123 | 0.0106 | 0.0305 * | 0.0224 |
| | - | - | [0.52] | [0.86] | [1.02] | [1.03] | [1.77] | [1.53] |
| **Share** | | | 7.47% | 18.62% | 27.83% | 42.91% | 69.00% | 90.69% |

**Table 5 - Carry Trade Performance During the Financial Crisis of 2008**

The table reports the monthly returns to carry trade portfolios for the period extending from July 2008 to December 2008 ($N$ = 6). Panel A presents the results when the allocations to individual currencies are spread-weighted (SPR). Panel B presents the results when the allocations to individual currencies are equal-weighted (EQL).

**Panel A: Spread-Weighted Portfolios**

| | **SPR** | **SPR (10$\delta$)** | **SPR (25$\delta$)** |
|---|---|---|---|
| **2008:7** | -0.0102 | -0.0118 | -0.0127 |
| **2008:8** | -0.0532 | -0.0333 | -0.0192 |
| **2008:9** | -0.0416 | -0.0354 | -0.0257 |
| **2008:10** | -0.0485 | -0.0246 | -0.0037 |
| **2008:11** | -0.0369 | -0.0424 | -0.0521 |
| **2008:12** | 0.0059 | 0.0123 | 0.0144 |

**Panel B: Equal-Weighted Portfolios**

| | **EQL** | **EQL (10$\delta$)** | **EQL (25$\delta$)** |
|---|---|---|---|
| **2008:7** | -0.0025 | -0.0040 | -0.0061 |
| **2008:8** | -0.0395 | -0.0221 | -0.0110 |
| **2008:9** | -0.0320 | -0.0265 | -0.0200 |
| **2008:10** | -0.0206 | 0.0010 | 0.0165 |
| **2008:11** | -0.0275 | -0.0321 | -0.0407 |
| **2008:12** | 0.0130 | 0.0158 | 0.0152 |

**Figure 4 - QQ-Plots of Carry Trade Portfolio Returns**

This figure depicts the quantiles of the monthly returns to different carry trade portfolios against the quantiles of the normal distribution. The portfolio returns are calculated monthly and the allocations to individual currencies are spread-weighted (SPR). The data spans over the period extending from January 1999 to August 2016 ($N$ = 212 months).

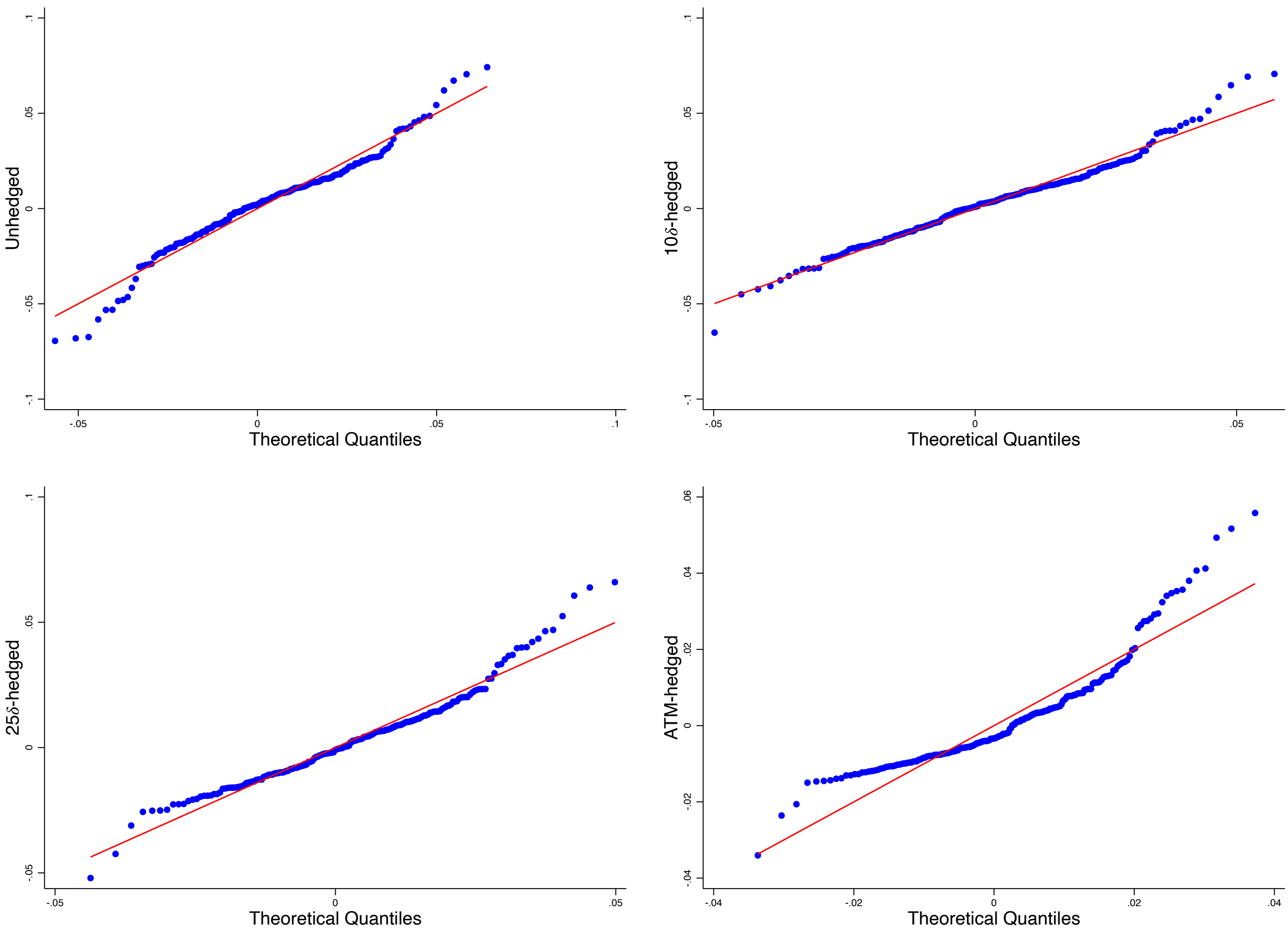


**Figure 5 - Crash-Neutral Currency Carry Trade Cumulative Returns**

This figure depicts the cumulative returns to the spread-weighted (SPR) unhedged, 10$\delta$-hedged, 25$\delta$-hedged, and ATM-hedged portfolios over the period extending from January 1999 to August 2016 ($N$ = 212 months). The shaded area corresponds to the 2008 financial crisis period.

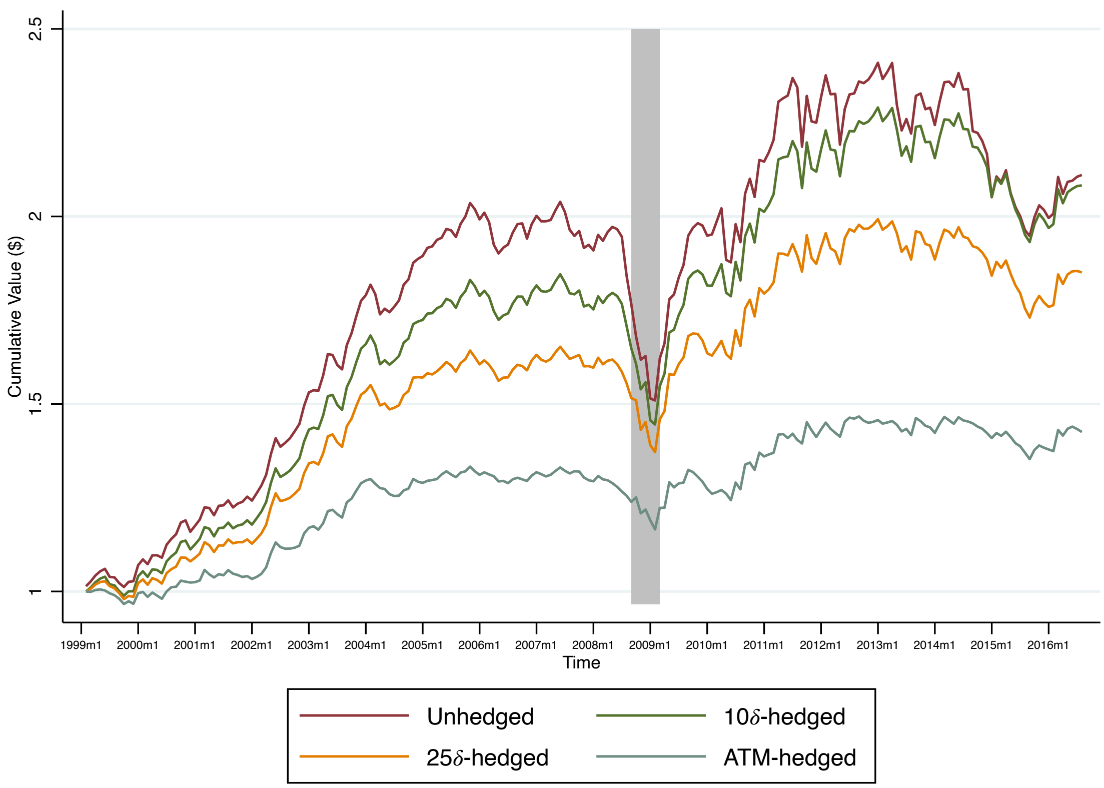
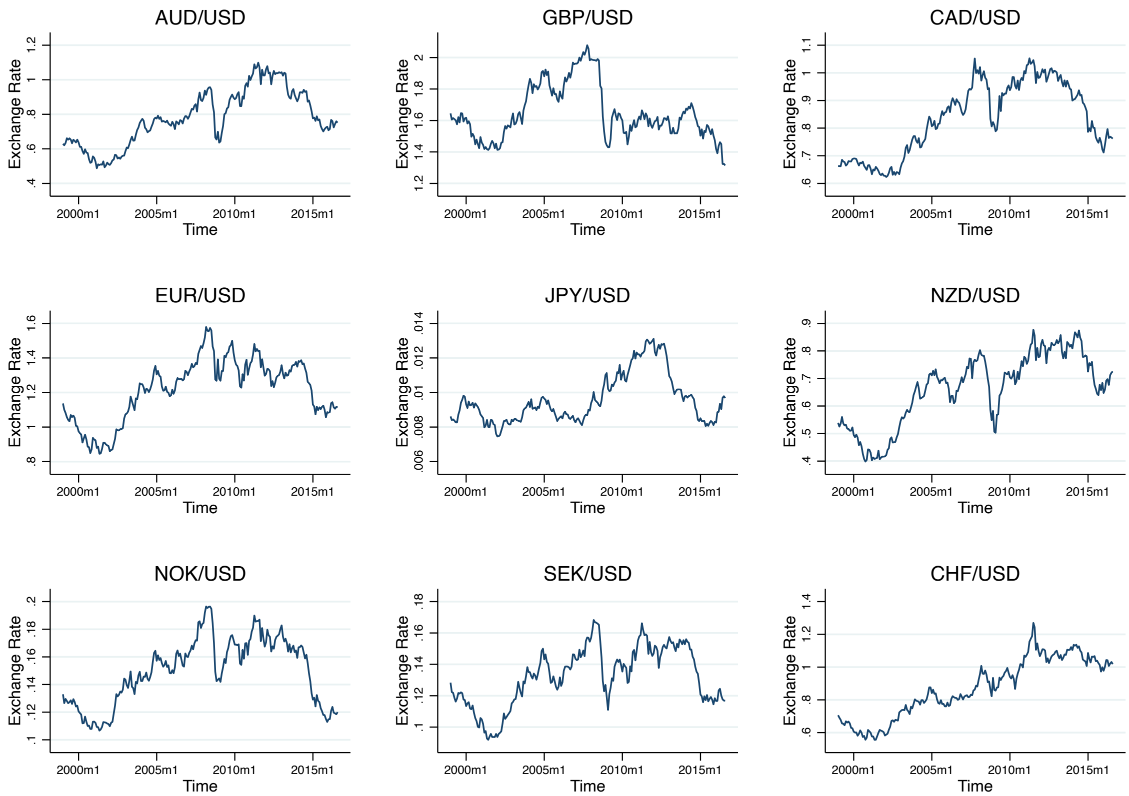


**Figure 6 - Historical Spot Exchange Rates**

This figure depicts the historical spot exchange rates of each of the nine G10 currencies against the U.S. dollar for the period extending from January 1999 to August 2016 ($N$ = 212 months).



# 6. CURRENCY CARRY TRADES AND EQUITY TAIL RISK

As presented in the literature review, a significant link has been demonstrated between equity market downside risk and the payoffs to the carry trade. In Section 5, I also present evidence that the carry trade experienced losses during the 2008 financial crisis, which suggests that the strategy is exposed to tail events in the equity market. In this section, I evaluate whether the excess returns to the carry trade can be understood as being compensation for the exposure to aggregate stock market jump risk. To do so, I construct a tradable jump risk factor, following Cremers, Halling, and Weinbaum (2015). I then perform a time-series analysis using the returns to the carry trade portfolios, as well as asset pricing tests using the cross-section of currency returns as test assets.

## 6.1. Construction of the risk factors

Following Cremers et al. (2015), I construct an investable option trading strategy using delta-neutral at-the-money straddles. As explained in the article, delta-neutral straddles are sensitive to small diffusive shocks due to their large vegas and sensitive to large jumps in the market due to the positive gamma of the options. Therefore, a strategy that is market-neutral, vega-neutral, and gamma-positive is exposed to jump risk while being insulated from volatility risk. In other words, the strategy I build is exposed to tail events, such as the 2008 crisis, while being largely insulated from business cycle fluctuations. As the gamma of an option is decreasing in time to maturity, the strategy can be built by combining long and short positions in market-neutral straddles of different maturities.

The straddle return is calculated using the following equation:

$$r_{MN} = \theta\, r_C + (1-\theta)\, r_P \tag{18}$$

where $r_{MN}$ is the market-neutral straddle return, $r_C$ is the return on the call, $r_P$ is the return on the put, and $\theta$ is the weight invested in the call.

I find $\theta$ by solving the following equation:

$$\theta\, \beta_C + (1-\theta)\, \beta_P = 0 \tag{19}$$

where $\beta_C$ is the call's market beta, and $\beta_P$ is the put's market beta[5].

As mentioned, the jump risk mimicking-portfolio (*JUMP*) is a market-neutral, vega-neutral, and gamma-positive strategy. It involves a long position in a market-neutral at-the-money straddle with maturity $T_1$ and a short position in $y$ market-neutral at-the-money

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[5] The option market betas are derived from the option deltas using the following formula:

$$\beta = \frac{S}{P} \cdot \delta$$

where $\beta$ is the call (put) option market beta, $S$ is the underlying asset price, $P$ is the call (put) option price, and $\delta$ is the call (put) option delta.

straddles with maturity $T_2$ $(T_1 < T_2)$. The $y$ is chosen to ensure that the strategy is vega-neutral; it is smaller than one since vega is increasing in time to maturity. The returns to the strategy are described by the following equation:

$$r_{JUMP} = r_{MN,T1} - y_{JUMP}\, r_{MN,T2} \tag{20}$$

where $r_{JUMP}$ is the return to the jump risk factor-mimicking portfolio, $r_{MN,Tt}$ is the return to the market-neutral straddle with maturity $T_t$, and $y_{JUMP}$ is the quantity of straddles chosen to make the vega of the overall strategy zero.

The straddle returns are calculated on a daily basis. For each maturity, at the end of each trading day in the sample, I choose the put and call option pair that is closest to being at-the-money, and that expires around one month ($T_1$) or two months ($T_2$) away from the trading date. The position is held for one day, and a new option pair is picked on the following day. The factor-mimicking portfolio returns are thus calculated on a daily basis and then compounded into monthly returns. Finally, I use data on S&P 500 index options from the Chicago Board Options Exchange (CBOE) to compute the returns. This differs from Cremers et al. (2015), as they use data on S&P 500 futures options from the Chicago Mercantile Exchange (CME) instead.

Panel A of Table 6 presents summary statistics on the *JUMP* factor's monthly returns for the period from January 1999 to August 2016. As in Cremers et al. (2015), the JUMP factor earns on average significantly negative returns. This is consistent with the expected negative market price of jump risk. Also, my factor's returns are 74% correlated to Cremers et al.'s (2015), suggesting that the usage of S&P 500 index options does not significantly affect the results.

I also include a dollar risk factor (*DOL*) in my analysis, introduced by Lustig et al. (2011). They define it as being the average portfolio return of a US investor who buys all currencies available on the market. In their article, they demonstrate that the risk factor accounts for a large fraction of the cross-sectional variation in currency returns. Thus, I control for the *DOL* factor in both the time-series and cross-sectional analysis to ensure that my results aren't driven by it. I build the *DOL* factor by calculating the equally weighted returns to shorting the dollar and going long each of the other G10 currencies. The factor's summary statistics are presented in Panel A of Table 6.

### 6.2. Time-series analysis

In this section, I analyze the relation between carry trade returns and the risk factors. To do so, I regress the carry trade portfolio returns on the returns to the different risk factors:

$$R_t = \alpha + \beta' F_t + \varepsilon_t \tag{21}$$

where $R_t$ is the monthly return on the studied carry trade portfolio and $F_t$ is the monthly return on the factors.

In all instances, since the risk factors are excess returns, it is possible to interpret the regression intercept ($\alpha$) as being the abnormal returns to the carry trade left unexplained by the model.

### *6.2.1. Carry trade exposures to traditional equity market risk factors*

I begin by analyzing the carry trade exposures to common equity market risk factors and regress excess returns to the spread-weighted portfolios[6] onto the Fama-French/Carhart factors (the market excess return *RMRF*, the size factor *SMB*, the book-to-market factor *HML*, and the momentum factor *UMD)*[7].

The regression results for the unhedged non-dollar-neutral portfolio are presented in the first column of Panel A (Table 7). The results reveal that the unhedged, spread-weighted portfolio has positive and highly statistically significant exposure to both the *RMRF* and *HML* factors. The beta associated with the *SMB* factor is also positive but statistically significant only at the 10% level. The regression alpha is statistically insignificant, suggesting that the model successfully explains the average returns to the carry trade. However, a 2.53% abnormal return remains economically significant. The adjusted $R^2$ is 0.25.

Panel B reveals that hedging does not affect the relation between the carry trade returns and the risk factors. Indeed, the hedged strategy exhibits positive loadings on the *RMRF*, *HML,* and *SMB* factors. The model is rejected at the 10% level, suggesting that the factors do a poorer job explaining the average excess returns when the portfolio is hedged against currency crash risk. The intercept is, however, similar in magnitude at 2.71%. The adjusted $R^2$ is also similar at 0.24. I present the regression results for the portfolios hedged using 25δ and at-the-money FX options in the Appendix (Table A.1); the results are similar when hedging is more aggressive.

Table 8 presents the results for the dollar-neutral spread-weighted portfolio. Once again, the portfolio returns exhibit positive and statistically significant exposure to the *RMRF* and *HML* factors. The *SMB* beta is now statistically insignificant. The null that the pricing error is zero cannot be rejected, and the model seems to successfully explain the portfolio's average excess return. However, the abnormal return is once again economically significant at 2.70%. The adjusted $R^2$ is also similar in magnitude at 0.20. Panel B of the table reveals that hedging does not significantly affect the portfolio's exposure to the factors.

In sum, these regressions reveal a relation between carry trade returns and equity market risk. Although after controlling for the exposure to these factors, the carry trade

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[6] I present the results when regressing the excess returns to the equal-weighted portfolios onto the factors in the Appendix (Tables A.3 and A.4). The main observations raised for the spread-weighted portfolios hold for the equal-weighted portfolios.

[7] The data is obtained on Kenneth French's website.

offers statistically insignificant abnormal returns, however these returns are not negligible, economically speaking.

### *6.2.2. Carry trade exposures to equity market jump risk*

I continue by studying the carry trade's exposure to equity jump risk. I first regress the returns to the carry trade portfolios on the returns to the jump risk factor-mimicking portfolio. I follow by controlling for the dollar risk factor and the Fama-French/Carhart factors to ensure the robustness of my results.

Column 2 of Panel A (Table 7) presents the results for the regression specification only involving the *JUMP* factor. The *JUMP* beta is negative and highly statistically significant, indicating that the severe losses to the carry trade portfolio are likely to coincide with tail events on the equity market. The regression alpha is statistically insignificant and around 36% lower than the portfolio's unconditional mean return. However, as for the Fama-French/Carhart model, a substantial abnormal return of 2.92% is left unexplained by the model. The adjusted $R^2$ is also much smaller than that of the Fama-French/Carhart model (0.06 and 0.25, respectively).

I present the results when controlling for the exposure to dollar risk in column 3. While the *JUMP* beta remains negative and highly statistically significant, it is smaller in magnitude. The *DOL* beta is positive and highly statistically significant. The model is rejected at the 10% level; however, this appears to be due to the model parameters being estimated more precisely. Indeed, the pricing error is lower in magnitude than for the model specification which only includes the *JUMP* factor (2.60% *versus* 2.92%). Controlling for the exposure to dollar risk sizeably improves the model fit as the adjusted $R^2$ goes from a value of 0.06 to a value of 0.41. This implies that the model's performance is mainly driven by the factor.

The fourth column presents the regression results when controlling for the exposure to both the *DOL* factor and the Fama-French/Carhart factors. The *JUMP* beta remains negative but is now statistically indistinguishable from zero; only the *RMRF*, *HML* and *DOL* betas are statistically significant. The pricing error is statistically insignificant, and it is the smallest in magnitude across all four regressions (2.15%). Furthermore, the model fit is 0.45, indicating that it does the best job explaining the variation in returns to the carry trade.

In Panel B, I present the results when regressing the returns to the spread-weighted 10δ-hedged portfolio onto the different risk factors. The features presented for Panel A carry over to Panel B. Indeed, the *JUMP* beta remains negative and statistically significant after hedging, even when controlling for dollar risk. Like in the case of the unhedged carry trade, it becomes statistically indistinguishable from zero after adding the Fama-French/Carhart factors to the model. The main difference between the hedged and unhedged portfolio regression results is that the model specification only involving the *JUMP* factor is rejected at the 10% level. However, the regression intercepts are similar in magnitude, implying that the model performance is comparable. I present the results for the 25δ-hedged and 50δ- hedged portfolios in the Appendix (Tables A.1 and A.2); the observations hold when hedging becomes more aggressive.

Table 8 presents the results for the dollar-neutral carry trade portfolio. The dollar-neutrality constraint doesn't seem to affect the results for the regression specification only involving the *JUMP* factor; the exposure to the risk remains negative and highly statistically significant. Controlling for the dollar risk factor does not materially change the results. The *JUMP* beta is still negative and highly statistically significant. The intercept remains not statistically significant, but the point estimate changes only slightly; hence the economic effect remains similar. The *DOL* beta is positive and statistically significant, which may be surprising given that the carry trade portfolio is constructed to be dollar neutral. It is important to note, however, that full dollar neutrality can only be achieved if all currencies have the same *DOL* betas. This is not the case empirically. This means that in a small cross-section, such as the one presented here, there could still be some remaining exposure to dollar risk. Adding the factor, however, does not improve the model fit as much as it does for the non-dollar-neutral portfolio. When also controlling for the Fama-French/Carhart factors, the *RMRF* and *DOL* betas are, once again, statistically significant, whereas the *HML* factor does not have any significant explanatory power. The *JUMP* beta is negative and statistically significant at the 5% level. This indicates that the factor's explanatory power on the carry trade returns is robust to controlling for the dollar risk factor and the Fama-French/Carhart factors, conditional on the strategy having no direct exposure to the USD. Panel B reveals that, once again, hedging the portfolio using FX options has no significant effect on the regression results.

In sum, the significant negative relation first found between carry trade returns and jump risk in the equity market does not hold after controlling for the dollar risk factor and the Fama-French/Carhart factors, in the case of the non-dollar-neutral carry trade. Conversely, the *JUMP* beta remains significant after controlling for the factors, conditional on the portfolio having no direct exposure to the USD. I continue my analysis by conducting asset pricing tests to determine if the *JUMP* factor is priced in the cross-section of currency returns.

## 6.3. Cross-sectional asset pricing tests

I continue the analysis by assessing whether jump risk is priced in the cross-section of currency returns. To so, I perform the Fama-Macbeth two-pass regression (Fama and Macbeth (1973)), using the individual currency excess returns as test assets.

In the first step, I run time series regressions of each currency *i*'s monthly excess return on a constant, and the risk factor returns:

$$R_{1,t} = \alpha_1 + \beta_{1,F_1} F_{1,t} + \cdots + \beta_{1,F_m} F_{m,t} + \varepsilon_{1,t} \tag{22}$$

$$R_{2,t} = \alpha_2 + \beta_{2,F_1} F_{1,t} + \cdots + \beta_{2,F_m} F_{m,t} + \varepsilon_{2,t}$$

$$\cdots$$

$$R_{n,t} = \alpha_n + \beta_{n,F_1} F_{1,t} + \cdots + \beta_{n,F_m} F_{m,t} + \varepsilon_{n,t}$$

where $R_{i,t}$ is currency *i*'s excess returns at time *t*, and $F_{j,t}$ is the returns to risk factor *j* at time *t*.

In the second step, I run cross-sectional regressions of the currency excess returns on the beta coefficients estimated in the first step, for each month in the sample (total of *T* months):

$$R_{i,1} = \gamma_{1,1}\hat{\beta}_{i,F_1} + \cdots + \gamma_{1,m}\hat{\beta}_{i,F_m} + u_{i,1} \tag{23}$$

$$R_{i,2} = \gamma_{2,1}\hat{\beta}_{i,F_1} + \cdots + \gamma_{2,m}\hat{\beta}_{i,F_m} + u_{i,2}$$

$$\cdots$$

$$R_{i,T} = \gamma_{n,1}\hat{\beta}_{i,F_1} + \cdots + \gamma_{n,m}\hat{\beta}_{i,F_m} + u_{i,T}$$

where the excess returns $R_{i,t}$ are the same as in the first step, and $\hat{\beta}_{i,j}$ is currency *i*' estimated exposure to factor *j*.

This results in a time series of $\gamma$ coefficient estimations which are used to calculate the factor risk prices. Following the literature, I do not include a constant in the second step. By doing this, I am imposing that a currency with no exposure to the risk factors has zero excess returns.

The Fama-Macbeth regression results are presented in Table 9. In Panel A, Column 1 presents the results when the model only includes the *JUMP* factor. The null that the pricing errors are jointly zero in the model cannot be rejected. The price of jump risk is negative. This means that investors seeking to hedge against tail events in the equity market will find currencies with a positive loading on jump risk attractive, and thus require lower expected returns. On the other hand, currencies whose returns covary negatively with jump risk demand a risk premium. The estimated price is, however, indistinguishable from zero. The cross-sectional fit is also relatively weak (adjusted $R^2$ of 0.34). This is not surprising as the model includes a single factor, and it is unlikely for the factor to be able to explain the both the variation in average excess returns across currencies and the average level of excess returns.

Column 2 presents the results when the model includes both the *JUMP* and *DOL* factors. Adding the *DOL* factor considerably improves the cross-sectional fit, as the adjusted $R^2$ nearly doubles to 0.60. Once again, the null that the pricing errors are jointly zero in the model cannot be rejected. The price of risk of the *DOL* factor is very low and statistically insignificant, revealing that the factor explains none of the cross-sectional variation in currency returns. The price of risk of the *JUMP* factor remains negative but is smaller in magnitude. It is once again statistically insignificant, suggesting that jump risk is not priced in the cross-section of currency returns. This result could perhaps be explained by the sample size which yields insufficient statistical power to reject the null hypothesis. Indeed, the sample period covers approximately 16 years and is much shorter when compared to other papers having conducted Fama-Macbeth regressions, namely Lustig et al. (2011) and Menkhoff et al. (2012) whose samples cover 28 and 26 years, respectively. Covering a longer period could conceivably help yield a more precise estimate and increase the power of the test.

I also present the results for the first stage of the Fama-Macbeth regression in Panel B. I focus on the *JUMP* and *DOL* factor model as it has the best cross-sectional fit. For all currencies, the pricing error is statistically indistinguishable from zero. The currency returns also load somewhat homogeneously onto the *DOL* factor, which confirms that it does not explain the cross-sectional variation in the currency returns. This suggests that the factor acts as a constant in the second stage of the regression, which explains the cross-sectional fit improvement when I include it in the model. The exposure to the *JUMP* factor becomes more negative somewhat monotonically as the average excess returns per currency increase, as is visible in Figure 7. Indeed, the *JUMP* beta is positive and statistically significant for the JPY and the CHF, both currencies with the lowest average excess returns. This suggests that these currencies provide a hedge against tail events in the equity market. Conversely, the coefficients are negative and statistically significant for the AUD and NZD, the two currencies with the highest average interest rates. The *JUMP* factor, however, does a poor job of explaining the returns for the non-extreme currencies, as evidenced by the statistically insignificant betas. This explains the risk price being statistically insignificant.

### *6.3.1. Robustness check*

As a robustness check, I run the same Fama-Macbeth regression, this time using the Lustig et al. (2011) portfolio excess returns as test assets[8]. In their article, they sort currencies into five portfolios on the basis of their forward discounts (or interest-rate differentials) versus the U.S. dollar at the end of each month in the sample. The portfolios are therefore ranked from low to high interest-rate, with portfolio 1 containing the lowest interest-rate currencies, and portfolio 5 containing the highest interest-rate currencies. I

[8] The data is obtained on Adrien Verdelhan's website.

focus on the portfolio excess returns they obtain using their smaller dataset, which contains the G10 currencies as well as the currencies of Belgium, Denmark, France, Germany, Italy, and the Netherlands. The *DOL* factor is calculated as the average excess return to the five portfolios.

The results of the first step of the regression are presented in Table 8 and are very similar to the results obtained when using individual currency returns as test assets. When looking at the results for the first step of the regression, there is somewhat of a pattern between the average excess returns to the portfolios and the betas, as is visible in Figure 7. The excess returns to the first and second portfolios, containing the lowest interest-rate currencies, have positive statistically significant exposure to both factors. The excess returns to the fourth and fifth portfolios, containing the highest interest-rate currencies, have negative statistically significant exposure to both factors. The third, or "middle" portfolio's *JUMP* beta is statistically indistinguishable from zero. Once again, the exposures to the risk do not successfully explain the cross-sectional variation in currency returns, and *JUMP* factor price of risk is negative, but statistically insignificant.

**Table 6 - Summary Statistics for the risk factor-mimicking portfolios**

This table presents the summary statistics for the jump (*JUMP*) and dollar (*DOL*) risk factors at the monthly frequency. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the descriptive statistics, and Panel B presents the pairwise correlations. The sample extends from January 1999 to December 2016 ($N$ = 212 months). The means, standard deviations, and Sharpe Ratios are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors are HAC robust.

**Panel A: Descriptive statistics**

| | JUMP | DOL |
|---|---|---|
| **Mean** | -0.5534 ***<br>[-3.41] | 0.0140<br>[0.69] |
| **Standard deviation** | 0.682 | 0.841 |
| **Sharpe Ratio** | -0.81 | 0.17 |
| **Skewness** | 2.68 | -0.13 |
| **Kurtosis** | 18.17 | 3.98 |

**Panel B: Pairwise correlations**

| | JUMP | DOL |
|---|---|---|
| **JUMP** | 1.00 | |
| **DOL** | -0.18 | 1.00 |

## Table 7 - Time Series Analysis: Non-Dollar-Neutral Portfolios

This table presents from regressions of the excess returns of the non-dollar-neutral spread-weighted portfolios onto a set of various risk factors. The Fama-French/Carhart factors include the excess market return *RMRF*, the size factor *SMB*, the book-to-market factor *HML*, and the momentum factor *UMD*. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the results for the unhedged portfolio. Panel B presents the results for the portfolio hedged using 10-delta options. The regressions are carried out over the period going from January 1999 to August 2016 ($N = 212$). The regression intercepts are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors are HAC robust.

**Panel A: SPR (unhedged)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\alpha$ | 0.0253<br>[1.48] | 0.0292<br>[1.50] | 0.0260 *<br>[1.67] | 0.0215<br>[1.45] |
| $\beta_{RMRF}$ | 0.234 ***<br>[5.79] | | | 0.0977 ***<br>[2.90] |
| $\beta_{SMB}$ | 0.073 *<br>[1.67] | | | 0.0581<br>[1.43] |
| $\beta_{HML}$ | 0.186 ***<br>[3.72] | | | 0.127 ***<br>[2.47] |
| $\beta_{UMD}$ | 0.002<br>[0.08] | | | -0.007<br>[-0.29] |
| $\beta_{JUMP}$ | | -0.030 ***<br>[-4.43] | -0.019 ***<br>[-3.91] | -0.011<br>[-1.62] |
| $\beta_{DOL}$ | | | 0.573 ***<br>[7.45] | 0.479 ***<br>[6.08] |
| **Adj. $R^2$** | 0.25 | 0.06 | 0.41 | 0.45 |

**Panel B: SPR (10δ)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\alpha$ | 0.0271 *<br>[1.82] | 0.0306 *<br>[1.79] | 0.0279 *<br>[1.97] | 0.0237 *<br>[1.77] |
| $\beta_{RMRF}$ | 0.199 ***<br>[5.54] | | | 0.082 **<br>[2.55] |
| $\beta_{SMB}$ | 0.072 *<br>[1.77] | | | 0.058<br>[1.57] |
| $\beta_{HML}$ | 0.170 ***<br>[3.84] | | | 0.120 **<br>[2.58] |
| $\beta_{UMD}$ | -0.003<br>[-0.12] | | | -0.011<br>[-0.48] |
| $\beta_{JUMP}$ | | -0.026 ***<br>[-4.74] | -0.017 ***<br>[-3.92] | -0.009<br>[-1.64] |
| $\beta_{DOL}$ | | | 0.492 ***<br>[7.26] | 0.409 ***<br>[6.00] |
| **Adj. $R^2$** | 0.24 | 0.06 | 0.38 | 0.43 |

**Table 8 - Time Series Analysis: Dollar-Neutral Portfolios**

This table presents from regressions of the excess returns of the dollar-neutral spread-weighted portfolios onto a set of various risk factors. The Fama-French/Carhart factors include the excess market return *RMRF*, the size factor *SMB*, the book-to-market factor *HML*, and the momentum factor *UMD*. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the results for the unhedged portfolio. Panel B presents the results for the portfolio hedged using 10-delta options. The regressions are carried out over the period going from January 1999 to August 2016 ($N$ = 212). The regression intercepts are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors are HAC robust.

**Panel A: SPR-$N (unhedged)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\alpha$ | 0.0270 | 0.0220 | 0.0200 | 0.0180 |
| | [1.31] | [1.00] | [0.98] | [0.89] |
| $\beta_{RMRF}$ | 0.259 *** | | | 0.163 *** |
| | [5.02] | | | [3.17] |
| $\beta_{SMB}$ | 0.045 | | | 0.024 |
| | [0.86] | | | [0.49] |
| $\beta_{HML}$ | 0.113 ** | | | 0.080 |
| | [2.03] | | | [1.46] |
| $\beta_{UMD}$ | -0.003 | | | -0.016 |
| | [-0.14] | | | [-0.65] |
| $\beta_{JUMP}$ | | -0.042 *** | -0.036 *** | -0.023 ** |
| | | [-5.28] | [4.74] | [-2.45] |
| $\beta_{DOL}$ | | | 0.355 *** | 0.221 *** |
| | | | [4.20] | [2.87] |
| **Adj. $R^2$** | 0.20 | 0.10 | 0.20 | 0.25 |

**Panel B: SPR-$N (10δ)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\alpha$ | 0.0268 | 0.0214 | 0.0198 | 0.0184 |
| | [1.45] | [1.12] | [1.09] | [1.02] |
| $\beta_{RMRF}$ | 0.205 *** | | | 0.124 *** |
| | [4.76] | | | [2.77] |
| $\beta_{SMB}$ | 0.046 | | | 0.028 |
| | [0.93] | | | [0.59] |
| $\beta_{HML}$ | 0.092 * | | | 0.065 |
| | [1.84] | | | [1.30] |
| $\beta_{UMD}$ | -0.011 | | | -0.022 |
| | [-0.48] | | | [-0.96] |
| $\beta_{JUMP}$ | | -0.036 *** | -0.031 *** | -0.022 ** |
| | | [-5.32] | [-4.52] | [-2.39] |
| $\beta_{DOL}$ | | | 0.278 *** | 0.170 *** |
| | | | [4.24] | [2.70] |
| **Adj. $R^2$** | 0.17 | 0.09 | 0.17 | 0.21 |

**Table 9 - Cross-Sectional Asset Pricing: Individual Currencies**

This table presents the results from the Fama-Macbeth regressions using individual currency excess returns as test assets. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the risk factor prices, as well as the $\chi^2$ test statistic for the null hypothesis that all pricing errors are jointly equal to zero with the corresponding p-value in parentheses. Panel B presents the results for the first stage of the regression. The regression constants are annualized. The sample extends from January 1999 to August 2016 (*N* = 212 months). The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors are HAC robust.

**Panel A: Factor Prices**

| | **(1)** | **(2)** |
|---|---|---|
| $\lambda_{JUMP}$ | -0.0608<br>[-1.12] | -0.0527<br>[-1.30] |
| $\lambda_{DOL}$ | | 0.0012<br>[0.72] |
| $\chi^2$ | 5.40<br>(0.80) | 5.36<br>(0.80) |
| **Adj. $R^2$** | 0.34 | 0.60 |

**Panel B: Factor Betas**

| | **JPY** | **CHF** | **EUR** | **SEK** | **CAD** | **GBP** | **NOK** | **AUD** | **NZD** |
|---|---|---|---|---|---|---|---|---|---|
| $\alpha$ | 0.0033<br>[0.15] | 0.0075<br>[0.48] | -0.0105<br>[-0.92] | -0.0206<br>[-1.64] | -0.0040<br>[-0.24] | -0.0099<br>[-0.63] | -0.0068<br>[-0.45] | 0.0137<br>[0.89] | 0.0273<br>[1.44] |
| $\beta_{JUMP}$ | 0.036 ***<br>[4.42] | 0.018 ***<br>[3.61] | 0.005<br>[1.21] | -0.008<br>[-1.24] | -0.014<br>[-1.52] | 0.005<br>[0.66] | -0.008<br>[-0.96] | -0.019 ***<br>[-3.58] | -0.015 **<br>[-2.01] |
| $\beta_{DOL}$ | 0.422 ***<br>[4.17] | 1.055 ***<br>[14.91] | 1.100 ***<br>[26.44] | 1.206 ***<br>[25.92] | 0.738 ***<br>[11.65] | 0.761 ***<br>[12.33] | 1.123 ***<br>[20.09] | 1.287 ***<br>[20.49] | 1.308 ***<br>[19.21] |
| **Adj. $R^2$** | 0.17 | 0.65 | 0.80 | 0.81 | 0.50 | 0.51 | 0.72 | 0.75 | 0.68 |

**Table 10 - Cross-Sectional Asset Pricing: Lustig, Roussanov, Verdelhan (2011) Portfolio Returns**

This table presents the results from the Fama-Macbeth regressions using the Lustig et al. (2011) portfolios' excess returns as test assets. The five portfolios are sorted according to each currency's forward discount versus the U.S. dollar. Portfolio 1 (PF1) contains the currencies with the lowest forward discounts, and portfolio 5 (PF5) contains the currencies with the highest forward discounts. The dataset includes the G10 currencies, as well as the currencies of Belgium, Denmark, France, Germany, Italy, and the Netherlands. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the risk factor prices, as well as the $\chi^2$ test statistic for the null hypothesis that all pricing errors are jointly equal to zero with the corresponding p-value in parentheses. Panel B presents the results for the first stage of the regression. The regression constants are annualized. The sample extends from January 1999 to August 2016 (*N* = 212 months). The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level. The standard errors are HAC robust.

| Factor Prices | | Factor Betas | | | | | |
|---|---|---|---|---|---|---|---|
| | | | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** |
| $\lambda_{JUMP}$ | -0.0864<br>[-1.79] | $\alpha$ | -0.0059<br>[-0.38] | -0.0119<br>[-1.16] | 0.0001<br>[0.05] | -0.0115<br>[-1.12] | 0.0288 **<br>[2.13] |
| $\lambda_{DOL}$ | 0.0010<br>[0.60] | $\beta_{JUMP}$ | 0.017 **<br>[2.58] | 0.008 **<br>[2.29] | 0.002<br>[0.44] | -0.015 ***<br>[3.88] | -0.012 **<br>[-2.58] |
| $\chi^2$ | 6.43<br>(0.27) | $\beta_{DOL}$ | 0.780 ***<br>[10.70] | 0.964 ***<br>[21.56] | 0.995 ***<br>[29.68] | 1.029 ***<br>[23.40] | 1.232 ***<br>[25.06] |
| **Adj. $R^2$** | 0.74 | **Adj. $R^2$** | 0.54 | 0.78 | 0.84 | 0.82 | 0.79 |

**Figure 7 - Average Currency Excess Returns vs JUMP Betas**

This figure plots the average currency excess returns against the exposures to jump risk ($\beta_{i,JUMP}$). The sample extends from January 1999 to August 2016 ($N$ = 212 months).

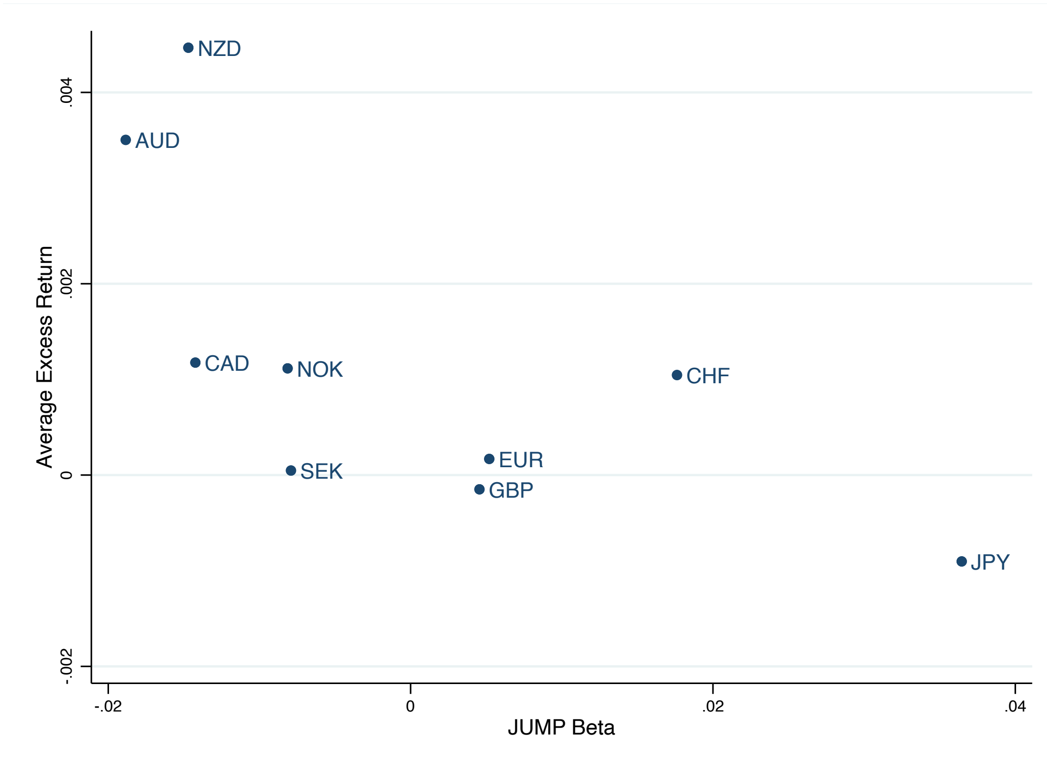
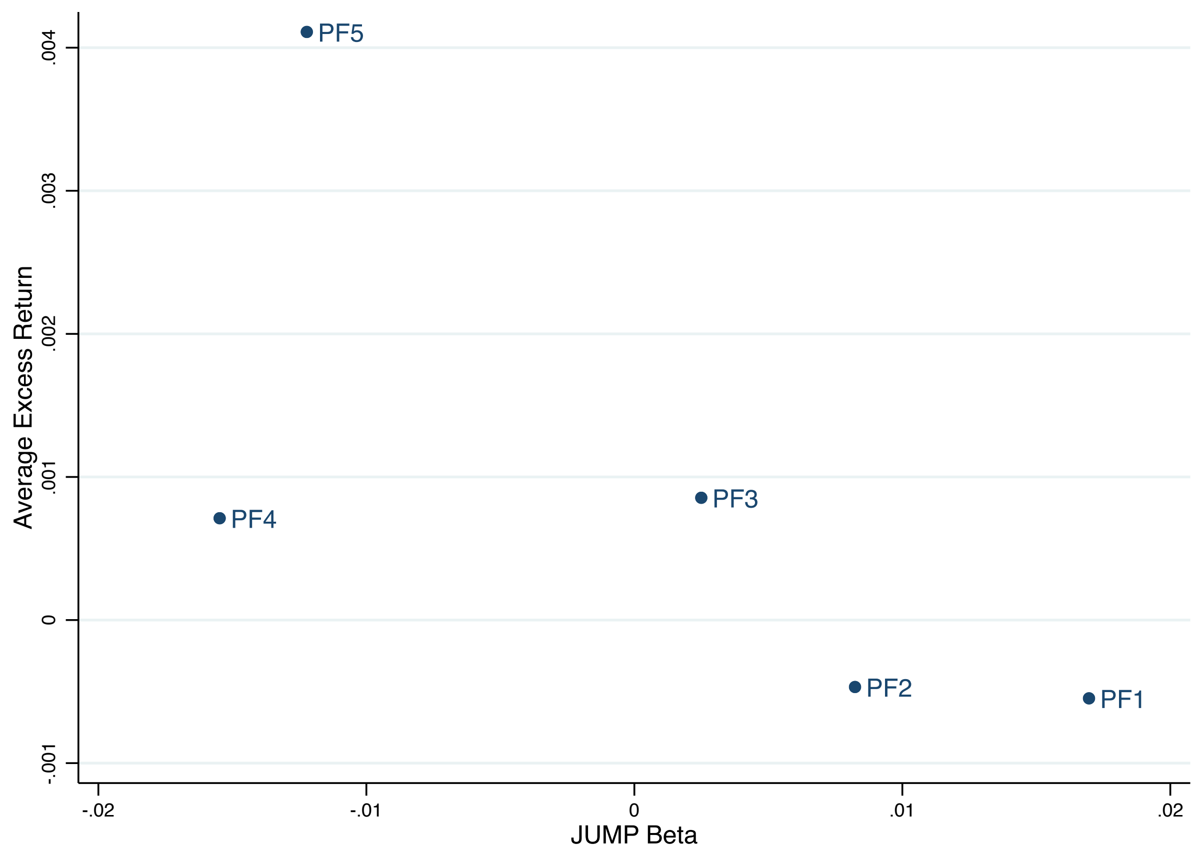


**Figure 8 - Average Portfolio Excess Return vs JUMP Betas**

This figure plots average portfolio excess returns against the exposures to jump risk ($\beta_{i,JUMP}$). The sample extends from January 1999 to August 2016 ($N$ = 212 months).



# 7. CONCLUSION

In this paper, I explore two possible explanations for the profitability of the carry trade. I first build on Jurek's 2014 paper by constructing crash-neutral carry trades and evaluate their performance over a longer sample period. The carry trades hedged using out-of-the-money foreign exchange options continue to deliver positive and statistically significant returns while exhibiting positive skewness. The average excess returns diminish as hedging becomes more aggressive, but the carry trade still delivers statistically significant returns when hedged using 25δ, and even at-the-money options in some cases. After comparing the returns to the unhedged and hedged carry trade portfolios, I find that crash risk premia account for at most 19% of the carry trade excess returns, an even lower share than found by Jurek (2014). This finding further confirms that crash risk plays a small role in rationalizing the high payoffs to the carry trade.

I also study whether equity tail risk can explain the profitability of the strategy. I begin by running time-series regressions of the carry trade portfolio returns on the returns to the jump risk factor I build using S&P 500 index options. I find that the portfolio returns have, in some cases, significant negative exposure to the risk factor but that the abnormal returns left unexplained by the factor are economically large. I also run a Fama-Macbeth regression using the individual currency returns as test assets. This cross-sectional analysis reveals that high yield currencies load negatively on the factor, while low-yield currencies have positive betas, suggesting that they provide a hedge against tail events in the equity market. However, the variation in exposures to the jump risk factor does not adequately capture the cross-sectional variation in currency returns, and the price of jump risk is not statistically significant.

# 8. APPENDIX

**Table A. 1 - Time Series Analysis: Hedged Non-Dollar-Neutral Portfolios**

This table presents from regressions of the excess returns of the non-dollar-neutral spread-weighted portfolios onto a set of various risk factors. The Fama-French/Carhart factors include the excess market return *RMRF*, the size factor *SMB*, the book-to-market factor *HML*, and the momentum factor *UMD*. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the results for the portfolio hedged using 25-delta options. Panel B presents the results for the portfolio hedged using 50-delta options. The regressions are carried out over the period going from January 1999 to August 2016 ($N$ = 212). The regression intercepts are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level.

**Panel C: SPR (25δ)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\alpha$ | 0.0229 * | 0.0262 * | 0.0239 * | 0.0203 |
| | [1.73] | [1.75] | [1.86] | [1.65] |
| $\beta_{RMRF}$ | 0.155 *** | | | 0.057 ** |
| | [4.73] | | | [1.86] |
| $\beta_{SMB}$ | 0.067 * | | | 0.057 * |
| | [1.88] | | | [1.74] |
| $\beta_{HML}$ | 0.145 *** | | | 0.102 *** |
| | [4.21] | | | [2.70] |
| $\beta_{UMD}$ | -0.008 | | | -0.014 |
| | [-0.37] | | | [-0.73] |
| $\beta_{JUMP}$ | | -0.022 *** | -0.013 *** | -0.007 |
| | | [-4.36] | [-3.21] | [-1.49] |
| $\beta_{DOL}$ | | | 0.413 *** | 0.349 *** |
| | | | [6.52] | [5.59] |
| **Adj. $R^2$** | 0.31 | 0.04 | 0.34 | 0.38 |

**Panel D: SPR (ATM)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\alpha$ | 0.0118 | 0.0152 | 0.0136 | 0.0108 |
| | [1.14] | [1.34] | [1.33] | [1.08] |
| $\beta_{RMRF}$ | 0.096 *** | | 0.0136 | 0.030 |
| | [3.45] | | [1.33] | [1.12] |
| $\beta_{SMB}$ | 0.048 * | | | 0.042 |
| | [1.71] | | | [1.64] |
| $\beta_{HML}$ | 0.102 *** | | | 0.073 ** |
| | [4.07] | | | [2.51] |
| $\beta_{UMD}$ | 0.000 | | | -0.003 |
| | [0.02] | | | [-0.18] |
| $\beta_{JUMP}$ | | -0.011 *** | -0.006 * | -0.003 |
| | | [-3.31] | [-1.97] | [-0.82] |
| $\beta_{DOL}$ | | | 0.282 *** | 0.246 *** |
| | | | [5.06] | [4.52] |
| **Adj. $R^2$** | 0.14 | 0.02 | 0.26 | 0.29 |

**Table A. 2 - Time Series Analysis: Hedged Dollar-Neutral Portfolios**

This table presents from regressions of the excess returns of the dollar-neutral spread-weighted portfolios onto a set of various risk factors. The Fama-French/Carhart factors include the excess market return *RMRF*, the size factor *SMB*, the book-to-market factor *HML*, and the momentum factor *UMD*. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the results for the portfolio hedged using 25-delta options. Panel B presents the results for the portfolio hedged using 50-delta options. The regressions are carried out over the period going from January 1999 to August 2016 ($N$ = 212). The regression intercepts are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level.

**Panel C: SPR-$N (25δ)**

| | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|
| $\alpha$ | 0.0212 | 0.0172 | 0.0159 | 0.0146 |
| | [1.21] | [1.01] | [0.95] | [0.86] |
| $\beta_{RMRF}$ | 0.139 *** | | | 0.068 * |
| | [3.46] | | | [1.67] |
| $\beta_{SMB}$ | 0.056 | | | 0.041 |
| | [1.20] | | | [0.92] |
| $\beta_{HML}$ | 0.072 | | | 0.047 |
| | [1.55] | | | [1.00] |
| $\beta_{UMD}$ | -0.014 | | | -0.023 |
| | [-0.57] | | | [-0.97] |
| $\beta_{JUMP}$ | | -0.027 *** | -0.023 *** | -0.017 ** |
| | | [-4.67] | [-3.80] | [-2.21] |
| $\beta_{DOL}$ | | | 0.233 *** | 0.167 ** |
| | | | [3.41] | [2.50] |
| **Adj. $R^2$** | 0.10 | 0.06 | 0.13 | 0.14 |

**Panel D: SPR-$N (ATM)**

| | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|
| $\alpha$ | 0.0061 | 0.0047 | 0.0039 | 0.0020 |
| | [0.40] | [0.32] | [0.27] | [0.13] |
| $\beta_{RMRF}$ | 0.081 ** | | | 0.032 |
| | [2.14] | | | [0.86] |
| $\beta_{SMB}$ | 0.042 | | | 0.033 |
| | [1.03] | | | [0.83] |
| $\beta_{HML}$ | 0.054 | | | 0.036 |
| | [1.33] | | | [0.87] |
| $\beta_{UMD}$ | 0.011 | | | 0.005 |
| | [0.41] | | | [0.19] |
| $\beta_{JUMP}$ | | -0.017 *** | -0.014 *** | -0.011 |
| | | [-3.33] | [-2.70] | [-1.69] |
| $\beta_{DOL}$ | | | 0.151 ** | 0.123 |
| | | | [2.03] | [0.13] |
| **Adj. $R^2$** | 0.04 | 0.03 | 0.07 | 0.06 |

**Table A. 3 - Time Series Analysis: Equal-Weighted Non-Dollar-Neutral Portfolios**

This table presents from regressions of the excess returns of the non-dollar-neutral equal-weighted portfolios onto a set of various risk factors. The Fama-French/Carhart factors include the excess market return *RMRF*, the size factor *SMB*, the book-to-market factor *HML*, and the momentum factor *UMD*. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the results for the unhedged portfolio. Panel B presents the results for the portfolio hedged using 10-delta options. Panel C presents the results for the portfolio hedged using 25-delta options. Panel D presents the results for the portfolio hedged using 50-delta options. The regressions are carried out over the period going from January 1999 to August 2016 ($N$ = 212). The regression intercepts are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level.

**Panel A: EQL (unhedged)**

| | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|
| $\alpha$ | 0.0146 | 0.0154 | 0.0139 | 0.0118 |
| | [1.39] | [1.30] | [1.33] | [1.20] |
| $\beta_{RMRF}$ | 0.130 *** | | | 0.064 *** |
| | [5.45] | | | [2.90] |
| $\beta_{SMB}$ | 0.037 | | | 0.028 |
| | [1.41] | | | [1.09] |
| $\beta_{HML}$ | 0.087 ** | | | 0.060 * |
| | [2.50] | | | [1.66] |
| $\beta_{UMD}$ | 0.001 | | | -0.004 |
| | [0.07] | | | [-0.21] |
| $\beta_{JUMP}$ | | -0.018 *** | -0.013 *** | -0.007 |
| | | [-4.44] | [-3.56] | [-1.57] |
| $\beta_{DOL}$ | | | 0.272 *** | 0.0215 *** |
| | | | [5.34] | [3.96] |
| **Adj. $R^2$** | 0.30 | 0.06 | 0.27 | 0.30 |

**Panel B: EQL (10δ)**

| | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|
| $\alpha$ | 0.0142 | 0.0150 | 0.0137 | 0.0117 |
| | [1.45] | [1.39] | [1.39] | [1.24] |
| $\beta_{RMRF}$ | 0.108 *** | | | 0.052 ** |
| | [4.58] | | | [2.21] |
| $\beta_{SMB}$ | 0.034 | | | 0.026 |
| | [1.38] | | | [1.09] |
| $\beta_{HML}$ | 0.080 ** | | | 0.056 * |
| | [2.49] | | | [1.69] |
| $\beta_{UMD}$ | 0.000 | | | -0.004 |
| | [0.03] | | | [-0.23] |
| $\beta_{JUMP}$ | | -0.015 *** | -0.011 *** | -0.007 |
| | | [-4.37] | [-3.36] | [-1.58] |
| $\beta_{DOL}$ | | | 0.231 *** | 0.183 *** |
| | | | [4.94] | [3.78] |
| **Adj. $R^2$** | 0.16 | 0.05 | 0.23 | 0.26 |

**Panel C: EQL (25δ)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| α | 0.0108 | 0.0119 | 0.0108 | 0.0089 |
| | [1.16] | [1.20] | [1.16] | [0.96] |
| $\beta_{RMRF}$ | 0.082 *** | | | 0.034 |
| | [3.35] | | | [1.37] |
| $\beta_{SMB}$ | 0.035 | | | 0.028 |
| | [1.50] | | | [1.28] |
| $\beta_{HML}$ | 0.072 *** | | | 0.052 * |
| | [2.65] | | | [1.80] |
| $\beta_{UMD}$ | 0.001 | | | -0.003 |
| | [0.05] | | | [-0.19] |
| $\beta_{JUMP}$ | | -0.012 *** | -0.008 *** | -0.005 |
| | | [-3.72] | [-2.71] | [-1.42] |
| $\beta_{DOL}$ | | | 0.194 *** | 0.160 *** |
| | | | [4.16] | [3.46] |
| **Adj. $R^2$** | 0.12 | 0.04 | 0.19 | 0.21 |

**Panel D: EQL (ATM)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| α | 0.0045 | 0.0057 | 0.0050 | 0.0033 |
| | [0.58] | [0.73] | [0.65] | [0.42] |
| $\beta_{RMRF}$ | 0.043 * | | | 0.009 |
| | [1.92] | | | [0.42] |
| $\beta_{SMB}$ | 0.025 | | | 0.021 |
| | [1.27] | | | [1.13] |
| $\beta_{HML}$ | 0.051 ** | | | 0.037 |
| | [2.38] | | | [1.61] |
| $\beta_{UMD}$ | 0.008 | | | 0.006 |
| | [0.58] | | | [0.42] |
| $\beta_{JUMP}$ | | -0.007 ** | -0.005 * | -0.003 |
| | | [-2.58] | [-1.76] | [-1.15] |
| $\beta_{DOL}$ | | | 0.124 *** | 0.113 *** |
| | | | [2.84] | [2.66] |
| **Adj. $R^2$** | 0.05 | 0.02 | 0.12 | 0.12 |

**Table A. 4 - Time Series Analysis: Equal-Weighted Dollar-Neutral Portfolios**

This table presents from regressions of the excess returns of the dollar-neutral equal-weighted portfolios onto a set of various risk factors. The Fama-French/Carhart factors include the excess market return *RMRF*, the size factor *SMB*, the book-to-market factor *HML*, and the momentum factor *UMD*. The *JUMP* factor is constructed following Cremers et al. (2015). It is the return to a market-neutral, vega-neutral, gamma-positive strategy. The *DOL* factor is the return to going short the U.S. dollar against an equally weighted basket of the nine remaining G10 currencies. Panel A presents the results for the unhedged portfolio. Panel B presents the results for the portfolio hedged using 10-delta options. Panel C presents the results for the portfolio hedged using 25-delta options. Panel D presents the results for the portfolio hedged using 50-delta options. The regressions are carried out over the period going from January 1999 to August 2016 (*N* = 212). The regression intercepts are annualized. The t-statistics are reported in square brackets. (***) indicates statistical significance at the 1% level, (**) indicates statistical significance at the 5% level, and (*) indicates statistical significance at the 10% level.

**Panel A: EQL-$N (unhedged)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\alpha$ | 0.0138 | 0.0087 | 0.0076 | 0.0075 |
| | [0.92] | [0.54] | [0.49] | [0.49] |
| $\beta_{RMRF}$ | 0.179 *** | | | 0.123 *** |
| | [5.24] | | | [3.50] |
| $\beta_{SMB}$ | 0.015 | | | 0.002 |
| | [0.43] | | | [0.05] |
| $\beta_{HML}$ | 0.055 | | | 0.037 |
| | [1.39] | | | [0.93] |
| $\beta_{UMD}$ | -0.014 | | | -0.022 |
| | [-0.65] | | | [-1.01] |
| $\beta_{JUMP}$ | | -0.029 *** | -0.025 *** | -0.016 ** |
| | | [4.49] | [-3.92] | [-2.12] |
| $\beta_{DOL}$ | | | 0.211 *** | 0.110 ** |
| | | | [3.87] | [2.26] |
| **Adj. $R^2$** | 0.21 | 0.08 | 0.15 | 0.21 |

**Panel B: EQL-$N (10δ)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| $\alpha$ | 0.0120 | 0.0068 | 0.0059 | 0.0060 |
| | [0.87] | [0.47] | [0.42] | [0.43] |
| $\beta_{RMRF}$ | 0.139 *** | | | 0.091 *** |
| | [4.68] | | | [2.86] |
| $\beta_{SMB}$ | 0.012 | | | -0.001 |
| | [0.34] | | | [-0.01] |
| $\beta_{HML}$ | 0.043 | | | 0.028 |
| | [1.24] | | | [0.79] |
| $\beta_{UMD}$ | -0.014 | | | -0.021 |
| | [-0.66] | | | [-1.00] |
| $\beta_{JUMP}$ | | -0.025 *** | -0.022 *** | -0.015 ** |
| | | [-4.38] | [-3.73] | [-2.16] |
| $\beta_{DOL}$ | | | 0.160 *** | 0.083 ** |
| | | | [3.84] | [1.98] |
| **Adj. $R^2$** | 0.13 | 0.07 | 0.12 | 0.16 |

**Panel C: EQL-$N (25δ)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| α | 0.0076 | 0.0041 | 0.0033 | 0.0028 |
| | [0.54] | [0.29] | [0.24] | [0.20] |
| $\beta_{RMRF}$ | 0.095 *** | | | 0.050 |
| | [2.84] | | | [1.53] |
| $\beta_{SMB}$ | 0.024 | | | 0.013 |
| | [0.68] | | | [0.39] |
| $\beta_{HML}$ | 0.040 | | | 0.025 |
| | [1.14] | | | [0.69] |
| $\beta_{UMD}$ | -0.007 | | | -0.013 |
| | [-0.33] | | | [-0.61] |
| $\beta_{JUMP}$ | | -0.019 *** | -0.016 *** | -0.012 * |
| | | [-3.56] | [-3.03] | [-1.94] |
| $\beta_{DOL}$ | | | 0.138 ** | 0.092 * |
| | | | [2.46] | [1.70] |
| **Adj. $R^2$** | 0.06 | 0.05 | 0.08 | 0.09 |

**Panel D: EQL-$N (ATM)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| α | -0.0022 | -0.0038 | -0.0042 | -0.0055 |
| | [-0.17] | [-0.31] | [-0.34] | [-0.42] |
| $\beta_{RMRF}$ | 0.046 | | | 0.014 |
| | [1.31] | | | [0.42] |
| $\beta_{SMB}$ | 0.020 | | | 0.012 |
| | [0.60] | | | [0.39] |
| $\beta_{HML}$ | 0.031 | | | 0.020 |
| | [0.89] | | | [0.57] |
| $\beta_{UMD}$ | 0.017 | | | 0.013 |
| | [0.80] | | | [0.60] |
| $\beta_{JUMP}$ | | -0.011 ** | -0.010 ** | -0.008 |
| | | [-2.32] | [-2.06] | [-1.56] |
| $\beta_{DOL}$ | | | 0.077 | 0.069 |
| | | | [1.17] | [1.09] |
| **Adj. $R^2$** | 0.01 | 0.02 | 0.03 | 0.02 |

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