Risk-Free Rates and Convenience Yields Around the World

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Abstract

This paper constructs risk-free interest rates implicit in index option prices for 9 of the major G10 currencies. We compare these rates to the yields of government bonds to provide international estimates of the convenience yield earned by safe assets. Average convenience yields across countries are highly correlated with the average interest rate in each country, ranging from -5 basis points in low-rate Japan to 61 basis points in high-rate Australia, with the moderate-rate US providing a middling 34 basis points. For each country, a covered interest parity (CIP) deviation constructed from its option-implied rates and those of the US is negative, with these negative CIP deviations growing sharply in periods of financial distress, including the 2020 covid crisis when convenience yields themselves remained moderate. We conclude that risk-free discount rates in the US are especially low due to its central position in the global financial system, particularly during financial crises, but that US safe assets do not earn an unusually large convenience yield in addition.

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I Introduction

In developed economies with minimal risk of sovereign default, government debt is a uniquely safe and liquid financial asset which plays a role similar to money. Government debt can be held by financial institutions to satisfy regulatory requirements, can be pledged as collateral for a low-interest-rate loan, and can be traded by uninformed agents with little or no fear of adverse selection. As documented in recent empirical work (Krishnamurthy and Vissing-Jorgensen, 2012, Nagel, 2016, van Binsbergen et al., 2021), government debt provides a convenience yield, a non-pecuniary value in addition to the present value of its future cash flows it pays, because of this special safety and liquidity.

While money-like assets in all currencies may earn a convenience yield, US government debt may be particularly special because it is denominated in the global reserve currency. A disproportionately large share of borrowing in international debt markets is denominated in dollars (Du and Schreger, 2021, Maggiori and Schreger, 2020), and international trade prices are often denominated in dollars even when countries outside the US trade with each other (Gopinath, 2016). This paper provides empirical estimates of the convenience yield of government debt denominated in 9 of the 10 G10 different currencies, allowing us to analyze how these convenience yields relate to the global role of the dollar (Jiang et al., 2021).

For each currency, we construct convenience yield estimates by comparing the yield on government debt to a risk-free rate implicit in the prices of risky assets that themselves are not safe and money-like. We do so using a unique new dataset from ICE, supplemented with additional observations from the Thompson Reuters Tick Database and OptionMetrics, that provides time-stamped intraday price quotes on European options written on the main stock index in each country since 2004. Exploiting the put-call parity relationship for European options[1], we are able to robustly infer risk-free discount rates implied by these option quotes without having to assume any specific asset pricing model. Crucial for our purposes, each

[1] Our approach follows the analysis of US option-implied rates in van Binsbergen et al. (2021).

individual option is a risky asset (and therefore does not provide a safe asset's convenience yield) even though a portfolio of such options can be used to construct a riskless payoff with a strategy called the box trade. The spread between the interest rate inferred from these options prices, which we call the box rate, and the yield on government debt is our measure of the convenience yield of government debt for each currency.

The average one-year maturity convenience yield in each country is highly correlated with the average level of interest rates in that country. High nominal rate currencies such as Australia and Norway, and Sweden have the largest convenience yields, while low rate currencies Switzerland and Japan negligible or even negative convenience yields. A cross-sectional regression of the average convenience yield of each country's one year government bond on its average one year nominal interest rate fits with an R-squared of .85, with a 1 percent higher rate predicting a 19 basis point higher convenience yield. The residual for the US in this regression is only 1.4 basis points, suggesting that the size of the US convenience yield is not unusual compared to the convenience yields of other countries.

Next, we use our risk-free rate estimates to construct covered interest parity (CIP) deviations. CIP is a no-arbitrage relationship that states that a foreign risk-free rate swapped into a synthetic dollar risk-free rate using currency forwards should equal the dollar risk-free rate. A literature going back to Du et al. (2018b)[2] shows that particularly since the 2008 financial crisis, CIP deviations are a persistent feature of the data, with dollar rates tending to be lower than synthetic dollar rates swapped from foreign currency. Our convenience yield estimates for each country rely only on interest rate spreads within that country, rather than on comparisons of rates between countries as previously studied by this literature. Our box rate estimates therefore allow us to decompose the CIP deviation between two countries' government bond yields into a CIP deviation for the countries' box rates (which we argue are free of the convenience yield for safe assets) and the difference in the countries' government bond convenience yields. This decomposition provides us with an estimate of how much of a

[2]See also Du et al. (2018a), Liao (2020), Krishnamurthy and Lustig, Engel and Wu (2021), Anderson et al. (2019), Wallen (2020).

government bond CIP deviation is due to the convenience yield of safe assets and how much is due to an arbitrage spread between the prices of risky assets in the two countries.

We find that the cross-section of government bond CIP deviations across countries is explained by the difference in countries' convenience yields while the overall level of CIP deviations is due to other forces. We replicate the finding of Du et al. (2018a) that the size of government debt CIP deviations across countries is explained well by the level of interest rates in each country. However, our box rate CIP deviations are negative for all countries and not closely related to interest rate levels. We show that a country's government CIP deviation is equal to its box rate CIP deviation plus the difference between its convenience yield and that of the US. As a result, the cross-section of government CIP deviations is explained by our result that convenience yields across countries are also explained by the level of interest rates. However, because the US does not have an unusually large convenience yield, we find that the size the average government debt CIP deviation is close to the average box rate CIP deviation we estimate. In this sense, we find that US assets are special, because on average they earn a low return compared to currency-hedged foreign assets as reflected in our negative box rate CIP deviations for every country. However, US safe assets do not in addition earn an abnormally large convenience yield on top of this.

In the time series, we find that convenience yields across countries rise during periods of financial distress. The time series of convenience yields in all countries seem disproportionately impacted by events in the US. The three most precisely estimated foreign convenience yields, U.K., Euro, and Switzerland, all experience convenience yield spikes above 100 basis points along with the US in the 2008-2009 global financial crisis, as well as elevation in the 2011-2012 European financial crisis and after the June 2016 vote for Brexit. During the 2020 covid crisis, convenience yields are mostly unaffected except for a brief period in late March 2020. US convenience yields fall near -20 basis points for roughly 2 weeks, while other currencies remain mostly flat.

We find that CIP deviations grow considerably during financial crises as well, but that this is mostly not driven by safe asset convenience yields. We show that government debt CIP deviations can be decomposed into a box rate CIP deviations plus the difference between a country's convenience yield and that of the US. Because box rate CIP deviations are constructed only from prices in the FX and option markets, they do not reflect a convenience yield specific to safe assets. While convenience yield levels do rise in crises, the convenience yield difference that enters a CIP deviation mostly does not. Increases in the size of government debt CIP deviations in crises are driven by increases primarily in box rate CIP deviations, with convenience yield differences if anything dampening this increase. Our time series and cross sectional results suggest an internally consistent story about the international role of US financial assets. In the cross section, we find that US assets have particularly low yields, reflected by every country's box rate yielding a higher dollar rate than the US box rate when combined with a currency hedge. However, US safe assets do not have an unusually large convenience yield on top of this. In the time series, we find that US rates fall below currency hedged foreign rates particularly during financial crises. Again, this not driven by US safe asset convenience yields growing larger than foreign convenience yields. In sum, we find the US assets are special, but not because specifically because of an unusual convenience yield for US safe assets.

A Conceptual Framework

This section presents a simple theoretical model related to Nagel (2016) that motivates our measurement exercise. An investor at $t = 0$ has access to assets that pay off at $t = 1$ who gains utility from consumption in each period as well as directly from its holding of safe/liquid/money-like assets. Assets $a_j : j \in 1 \ldots n$ are available for purchase, where asset j has a price p_j at time 0, pays a random variable δ_j at time 1, and provides d_j units of "convenience" from being money-like per unit of currency invested in it. Let q_j denote the quantity of asset j chosen by the investor. The investor has preferences

$$u(C_0) + \beta E u(C_1) + v(D) \tag{1}$$

where C_t is consumption at time t and $D = \sum_{j=1}^{n} p_j q_j d_j$ is the total stock of convenience provided by holding money-like assets. The investor is endowed with wealth W and chooses the quantities q_j of assets it holds to maximize its utility in equation 1 subject to the following three constraints:

$$C_0 + \sum_{j=1}^{n} q_j p_j = W, \qquad C_1 = \sum_{j=1}^{n} q_j \delta_j, \qquad D = \sum_{j=1}^{n} p_j q_j d_j. \tag{2}$$

The first two constraints in equation 2 are budget constraints at times 1 and 2, while the third equation gives the quantity of convenience provided by the investor's portfolio. The most money-like asset, cash, is normalized to provide one unit of safety ($d_i = 1$) and pays a (nominal) interest rate of 0.[3]

The investor's first order condition for its quantity q_j of asset j is given by

$$p_j = \frac{\beta E[u'(C_1)\delta_i] + v'(D) p_j d_j}{u'(C_0)}. \tag{3}$$

In particular for a risk-free asset j that pays $\delta_j = 1$ and provides d_j units of convenience, its interest rate i_j must satisfy

$$1 = (1 + i_j)\frac{\beta E u'(C_1)}{u'(C_0)} + \frac{v'(D)}{u'(C_0)} d_j. \tag{4}$$

The two extreme special cases of this first order condition are for cash, which provides $d_j = 1$ units of asset safety and pays an interest rate of 0 (and thus has price $p_j = 1$), and a "not convenient asset" which pays the interest rate i_{nc} and provides $d_a = 0$ units of convenience.

[3] For simplicity, we assume inflation is 0 so real and nominal rates are identical. Our key result in equation 7 also holds when inflation can occur, though it takes slightly more algebra to show.

We have for these two cases

$$1 = (1 + i_{nc})\frac{\beta E u'(C_1)}{u'(C_0)} = \beta E \frac{u'(C_1) + v'(Q)}{u'(C_0)}. \tag{5}$$

Equation 5 implies

$$\frac{\beta E u'(C_1)}{u'(C_0)} = \frac{1}{1 + i_{nc}}, \qquad 1 - \frac{1}{1 + i_n c} = \frac{v'(D)}{u'(C_0)}. \tag{6}$$

Plugging the two expressions in equation 6 into equation 5 and rearranging yields our main result:

$$\underbrace{i_{nc} - i_j}_{\text{convenience yield of asset j}} \qquad = i_{nc} q_a. \tag{7}$$

On the left hand side of equation 7 we have the convenience yield of asset j- the rate of return investors are willing to forgo in order to hold the asset instead of one that provides no asset convenience. On the right hand side we have the quantity q_j of convenience the asset provides times the nominal interest rate i_{nc}, which can be interpreted as the "price of convenience." This is because an investor who holds cash instead of a no convenience asset loses the interest payment i_{nc} in exchange for a quantity $q_j = 1$ of convenience provided by holding cash.

Near-Money Assets and Convenience Yields

While the quantity of convenience d_j provided by asset j is exogenous, with some reasonable assumptions about how q_j is determined, the model suggests an approch to estimating convenience yields. In particular, if we assume that q_j decreases smoothly in the riskiness of an asset before eventually reaching $q_j = 0$ for assets that do not resemble low-default-risk debt securities, figure 1 summarizes asset prices in our model. Assets that provide no convenience have an expected return that is a linear function of the covariance of its payoff's with the investor's stochastic discount factor (SDF) $\frac{\beta u'(C_1)}{u'(C_0)}$. Assets that provide convenience have an expected return strictly lower than the one implied by this linear relationship, with the spread increasing in the safety/convenience of the asset. As illustrated in figure 1, comparing

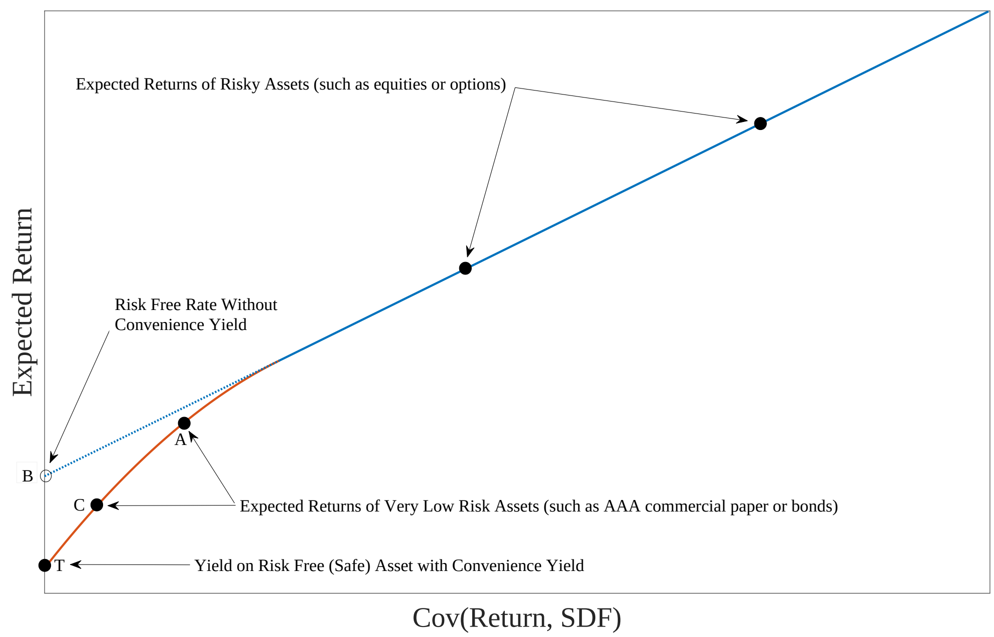

Figure 1. Risk and return with a special demand for safe assets (convenience).

the yield of a Treasury security to the yield of a slightly less safe or less liquid asset can either overestimate or underestimate the Treasury's convenience yield. On the one hand, nearly safe assets such as the debt of banks or AAA rated companies may have their returns reduced by the fact that they are somewhat money-like and provide convenience themselves. On the other hand, these low risk assets may not be perfectly riskless, and the credit risk premium they earn increases their expected return. These two forces combined can result in an expected return above (as shown by point A) or below the convenience-yield-free risk-free rate (as shown by point C). Motivated by this figure, this paper attempts to estimate a convenience-yield-free risk-free rate by inferring a risk-free rate implicit in the prices of risky assets, which provide no convenience yield and therefore live on the blue line in figure 1.

In our framework, such a risk-free rate is given by point B in the figure, and the spread between point B and the Treasury yield at point T correctly identifies the convenience yield of a Treasury security.

B Constructing risk-free rates from risky assets

We infer risk-free rates using the put-call parity relationship for European options. At time t, we observe the prices of a cross section of options that mature in T periods and have strike prices $K_{i,j}$ denominated in currency j for $i = 1, ...N$. We aim to infer the interest rate $r_{j,t,T}$ on a riskless investment in currency j at time t that matures in T implied by these option prices. If we denote the prices at time t of a put and call of strike price K_i that mature in T periods by $p_{i,j,t,T}$ and $p_{i,j,t,T}$, the put-call parity relationship can be written as

$$p_{i,j,t,T} - c_{i,j,t,T} = (\mathcal{D}_{j,t,T} - S_{j,t}) + \exp(-r_{j,t,T}T)K_{i,j}. \tag{8}$$

In this expression, $S_{j,t}$ is the price of the underlying asset on which the options in currency j are written and $\mathcal{D}_{j,t,T}$ is the present value of dividends paid by the underlying asset before the options mature. Put-call parity for European options follows only from the absence of arbitrage and does not rely on any specific option pricing model.

This put-call parity expression implies that in the absence of arbitrage, there is a perfect linear relationship between the difference $p_{i,j,t,T} - c_{i,j,t,T}$ between the prices of puts and calls and the strike price $K_{i,j}$. The slope of this line equals the discount factor $\exp(-r_{j,t,T}T)$ from which we can infer the interest rate $r_{j,t,T}$. We therefore can estimate our option-implied interest rates from a cross-sectional linear regression of $p_{i,j,t,T} - c_{i,j,t,T}$ on $K_{i,j}$. By estimating this regression separately for options whose strike prices are denominated in different currencies, we obtain risk-free rate estimates for each currency. We can write our linear put-call parity expression as

$$p_{i,j,t,T} - c_{i,j,t,T} = \alpha_{j,t,T} + \beta_{j,t,T} K_{i,j} + \varepsilon_{i,j,t,T}. \tag{9}$$

where an estimate of the slope $\beta_{j,t,T} = \exp(-r_{j,t,T} T)$ allows us to infer the risk-free rate $r_{j,t,T}$. Potential deviations from put-call parity are reflected in the error term $\varepsilon_{i,j,t,T}$, which should be extremely small in a market approximately free of arbitrage opportunities. We estimate $\beta_{j,t,T}$ with the standard Ordinary Least Squares estimator

$$\beta_{OLS} = \frac{\sum_i \left((p_{i,j,t,T} - c_{i,j,t,T} - \bar{p} - \bar{c})(K_{i,j} - \bar{K}) \right)}{\sum_i (K_{i,j} - \bar{K})^2}, \tag{10}$$

where a variable with a bar over it denotes its sample average at a given point in time in a given currency. Our implied interest rate estimate is then

$$r_{j,t,T} = -\frac{1}{T} ln(\beta_{OLS}) \tag{11}$$

In addition to providing an interest rate estimate, a measure of fit of this regression (such as its R-squared) provides a useful measure of the size of arbitrage spreads in an option market. Only an R-squared extremely close to 1 provides a precise interest rate estimate. We use the R-squared of this regression as a measure of frictions in an option market that result in arbitrage opportunities. This measure can be used both to compare countries to each other to see which has the most precise option-implied interest rate estimates as well as over time to document periods of market illiquidity.

We estimate the option-implied risk-free rates using quote data from the Chicago Board Options Exchange (CBOE) for the dollar and from the Intercontinental Exchange (ICE) for foreign currencies. These indices are: the S&P 500 for the US, the STOXX 50 for Europe, the Swiss Market Index for Switzerland, the FTSE 100 for the UK, the OMX Stockholm 30 for Sweden, the OBX for Norway, the TSX 60 for Canada, the Nikkei 225 for Japan, and the ASX 200 for Australia.[4] When estimating the option-implied risk-free rates we impose minimal filters on the data. We start with the raw quote data from CBOE or ICE and then compute one-minute medians across all quotes with non-zero bid and ask prices, non-zero bid and ask quote sizes, and a positive bid-ask spread. We then compute minute-level regressions for each currency and maturity and collapse our estimates to daily medians of the box rates for each currency. When data is not available from CBOT or ICE, we backfill with one-minute quote data from the Thomson Reuters Tick History database and then with daily data from the OptionMetrics database.

We illustrate our estimation approach in figure 2 below. The dots in the figure are the difference between put and call prices of the same strike price and the same one year maturity. To visual accuracy, the dots live along a line, reflecting the fact that put-call parity holds quite well in our data. Fitting a linear regression to these data points results in an R-squared of .9999998 and an implied interest rate of minus 48 basis points. To construct our daily time series of interest rates, we run these regressions minute-by-minute throughout the day and take a median of the resulting rate estimates. To minimize the impact of outliers, we only use regressions with an R-squared of at least .99999, which for some currencies results in occasional days with no interest rate estimate at all. Finally, the interest rates we estimate have maturities that are determined by the schedule on which option contracts expire. To go from these fairly irregular maturities to a fixed grid of 3-month, 6-month, 1-year, 2-year, and 3-year interest rates, we use linear interpolation, taking a weighted average of the two option-implied rates closest to any given maturity. This is illustrated in figure 3 below. For comparison, we include a Nelson-Siegel-Svensson (NSS) yield curve the ECB fit to AAA bonds in this figure. The difference between these two curves at each maturity is our European convenience yield estimate for that maturity.

[4] To our knowledge, there are no exchange-traded European options written on the main New Zealand stock index (see https://www.nzx.com/markets/NZCX/), so the New Zealand Dollar is the only G10 currency for which we do not have option-implied interest rates.

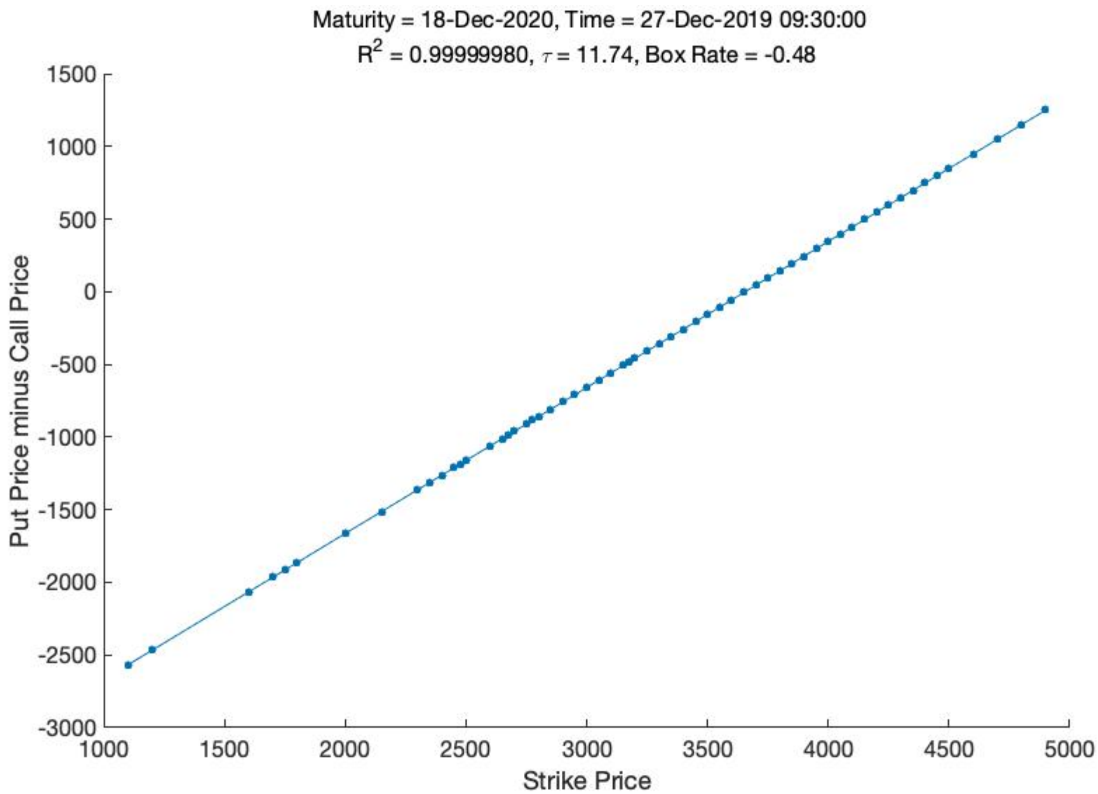

Figure 2. Data Example: Linear Relationship between Put Minus Call Prices and Strike Prices of Options

C Convenience Yields Around The World: Cross-Sectional Evidence

This section presents our results on the average size of our convenience yield estimates in G10 countries with two main results. First, the convenience yield we estimate for the US bonds is roughly the average convenience yield across the G10 countries at 34 basis points. Second, each country's average convenience yield is closely related to its average nominal interest rate, with higher rate countries having higher convenience yields.

Table 6 presents the sample averages of our convenience yield estimates across currencies and across maturities. The first panel presents results comparing our option-implied rates to bond yields (or yields inferred from a bond yield curve) while the second panel presents results comparing our option-implied rates to the yields of shorter maturity bills. US bonds have an average convenience yield of roughly 34 basis points, with a nearly flat

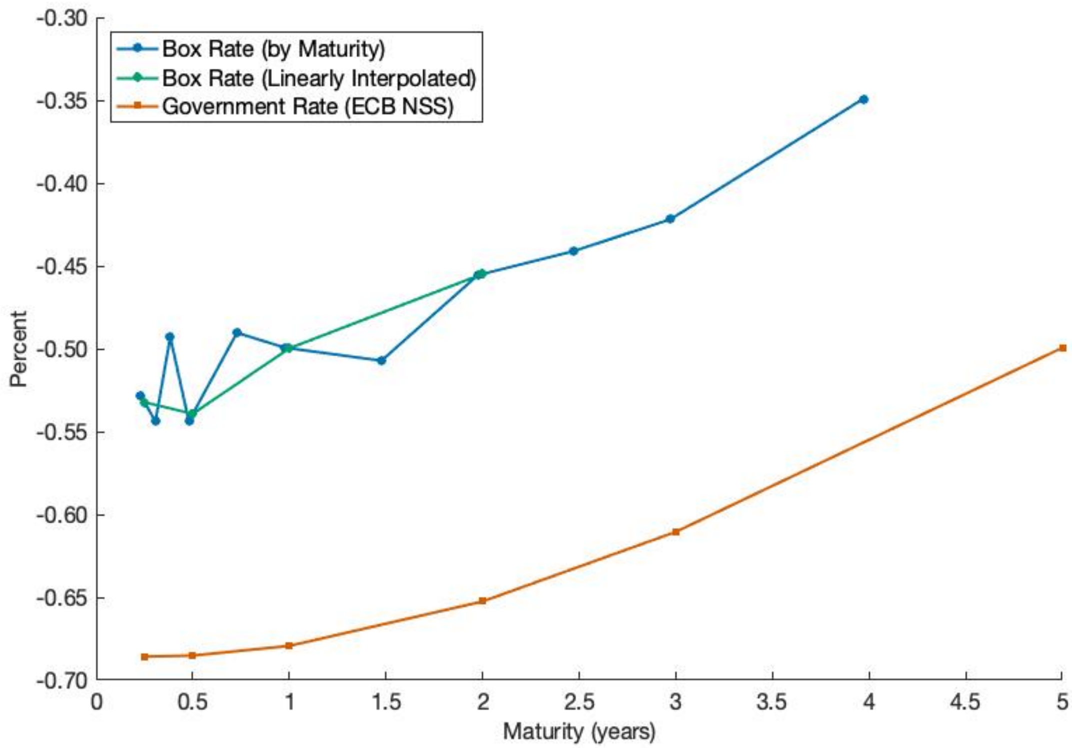

Figure 3. Data Example: Linear Interpolation of Option-Implied Yields

term structure of convenience yields across maturities. This is below the convenience yields of four currencies (Australia, Norway, Canada, Sweden) and above that of four (UK, Euro, Switzerland, Japan). By our measure, the US seems to have a mean convenience yield that is near the middle of that in other countries.

As shown in figure 4, the cross section of mean convenience yields across countries is quite well explained by the average nominal interest rate in each country. The largest convenience yields in table 6 are those of Australia, ranging from 50 to 61 basis points across maturities, and the smallest is that of Japan which is negative 5 to negative 18 basis points. These countries also respectively have the highest and lowest average nominal interest rates in our sample as seen in figure 2. As shown in table 6, a regression of each country's average 1 year convenience yield (with 6 months used for Sweden and Norway due to a lack of 1 year maturity options) yields a slope parameter of .191411, and a R-squared of .848. This suggests that convenience yield levels may be related to the carry trade, in which

Table 1

Summary statistics. Average Convenience Yields. Newey-West Standard Errors based on 100 day lag and number of observations in parentheses.

Country	3 Month	6 Month	1 Year	2 Year	3 Year
USA	.0032 (.0003,5823)	.0035 (.0002,5961)	.0034 (.0002,5834)	.0035 (.0003,3667)	
UK	.0022 (.0008,4529)	.0030 (.0005,4530)	.0035 (.0003,4530)	.0038 (.0011,4530)	
Euro	.0029 (.0004,4751)	.0029 (.0003,4890)	.0027 (.0003,4982)	.0024 (.0002,4967)	.0022 (.0002,4855)
Switzerland			.0002 (.0002,5291)	.0015 (.0003,4559)	.0022 (.0002,4442)
Canada	.0047 (.0009,2631)	.0036 (.0004,2639)	.0036 (.0002,1855)	.0029 (.0002,1369)	
Australia	.0051 (.0011,1931)	.0050 (.0010,1964)	.0061 (.0006,684)		

Country	3 Month	6 Month	1 Year
USA (Bill)	.0050 (.0003,6923)	.0048 (.0003,5966)	.0047 (.0004,4158)
UK (Bill)	.0023 (.0005,3464)	.0015 (.0003,769)	
Euro (Bill)		.0030 (.0004,4783)	.0022 (.0003,3540)
Japan (Bill)	-.0015 (.0013,1818)	-.0018 (.0013,1549)	-.0005 (.0018,1371)
Norway (Bill)	.0050 (.0005,2400)	.0050 (.0006,2015)	
Sweden (Bill)	.0038 (.0005,3002)	.0048 (.0006,3090)	
Switzerland (Bill)	.0025 (.0005,4869)		
Canada (Bill)	.0050 (.0009,2701)	.0039 (.0004,2725)	.0036 (.0016,1921)

international investors borrow in low interest rate countries (like Japan) and lend in high interest rate countries (like Australia). In addition, this is consistent with our conceptual framework that follows Nagel (2016). Nagel shows in a long time series of US data that the sizes of convenience yields are closely related to the level of nominal interest rates. Our result is complementary, providing evidence for the same hypothesis in a cross section of countries rather than a single country's time series. In addition, the US observation has the smallest residual in the cross sectional regression (1.4 basis points), further suggesting that its mean convenience yield is not unusual compared to the cross section of other countries.

Table 2. Cross Country Regressions of Interest Rate Spreads on Average Treasury Rates, 1-Year Maturity

Coefficient	LIBOR-Treasury Spread	Box-Treasury Spread
Intercept	0.00341 (0.00072)	0.00028 (0.00056)
Slope	0.04883 (0.04041)	0.19411 (0.03108)
R-squared	0.173	0.848

While our estimated convenience yield magnitudes are highly correlated with the level

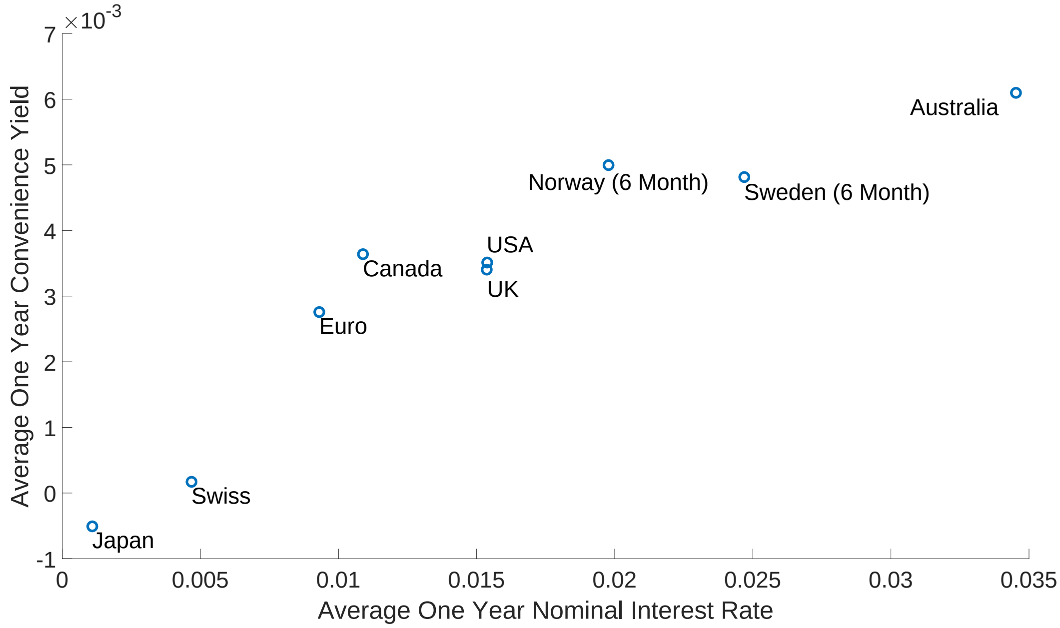

Figure 4. Average One-Year Convenience Yields and One-Year Government Yields Across Countries

of nominal interest rates across countries, this relationship is weaker for the commonly used LIBOR rate. LIBOR is a survey-based measured of the rate at which banks can raise unsecured debt. Unsecured bank debt is a low risk asset, and therefore may provide some convenience yield, but it also has some credit risk reflected in its pricing. In a cross-sectional regression of LIBOR-Treasury spreads across countries, we find a smaller slope coefficient of just .04883 and an R-squared of .173. This implies that a one percentage point higher Treasury rate in a country is associated with 19.4 basis points larger Box-Treasury spread (so the Box rate is 119.4 basis points higher) but only a 4.8 basis point larger LIBOR-treasury spread. If we believe that cross-sectional differences in the creditworthiness of banks in each country are reflected in the levels of their LIBOR rates, it is logical that a country's nominal interest rate is not a particularly strong predictor of the level of LIBOR-Treasury spreads. In addition, the lower slope for LIBOR is also consistent with our model's implication for how an asset that is more money-like than our box rate should be priced. If we apply equation 7 to LIBOR, Box rates, and Treasury yields and abstract from credit risk in LIBOR, we obtain

$$(i_{box} - i_{Treasury}) - (i_{LIBOR} - i_{Treasury}) = i_{nc}[q_{LIBOR} - q_{box}]. \tag{12}$$

If LIBOR provides more convenience than box rates, so $q_{LIBOR} > q_{box}$ (which includes the special case $q_{box} = 0$ if we truly have that the Box rate is i_{nc}), an increase in interest rates should make the Box-Treasury spread increase more than the LIBOR-Treasury spread, just as we observe in the data.

Precision of Estimated Rates

For our box rates to be precisely estimated, it is crucial that the put-call parity relationship that it exploits to hold well in the data. One measure of the degree to which put-call parity holds is the R-squared of the regression in equation 9, since put-call parity holds exactly if and only if this regression has an R-squared of 1. Table 3 presents summary statistics on the R-squared of this regression across countries. For each country, we exclude observations with an R-squared below .9999 and take a median of the remaining regressions within each day. The table then reports the time series average of this daily median R-squared for each country. Put-call parity holds most precisely in US data while also holding extremely well for Europe, Switzerland, and the UK. The regression gradually drops off in precision with the lowest R-squared being .9999548 for Australia. This R-squared is still quite close to 1, suggesting that although Australian option prices may feature some microstructure noise, the observed violations of put-call parity are not extreme. While we believe the data is precise enough to use for cross-sectional comparisons in all countries, our later analysis of higher frequency time series variation will restrict itself to the countries with the highest R-squares to minimize the impact of noise.

Table 3

Summary Statistics : Average of daily median of R-squared of put-call parity regression in equation 9 used to estimate box rates.

Country	Stock Index	Mean R-Squared	N	Start	End
Australia	XJO	0.9999548	4578	1/2/2004	7/27/2020
Norway	OBX	0.9999738	4464	1/3/2005	7/27/2020
Japan	N225	0.9999853	4098	1/6/2005	7/27/2020
Sweden	OMXS30	0.9999871	4184	1/3/2005	6/30/2020
Canada	TX60	0.9999901	3416	1/1/2010	3/6/2020
UK	UKX	0.9999907	4144	1/2/2004	7/27/2020
Switzerland	SMI	0.9999919	4493	1/2/2004	7/27/2020
Europe	STOXX	0.9999962	4587	1/2/2004	7/27/2020
US	SPX	0.9999995	4781	1/2/2004	7/1/2020

D Covered Interest Parity: Convenience Yields and Market Segmentation

This section presents covered interest parity deviation estimates using our option-implied rates and for government debt. Covered interest parity (CIP) is a no-arbitrage relationship that states that risk-free interest rates in a home currency (which we take to be the dollar) \$ and foreign currency f must satisfy

$$exp(ni_{\$}) = \frac{F}{S} exp(ni_f)$$
$$i_{\$} = \frac{1}{n}(log(F) - log(S)) + i_f$$

where S is the spot exchange rate between the two currencies, n is the number of periods for which the interest compounds, and F is the forward exchange rate at the time of maturity. Exchange rates here are measured in dollars per unit of foreign currency. The relationship reflects the fact that home currency can be swapped into foreign currency today at exchange rate S, invested at the foreign rate i_f, and then swapped back to home currency at forward rate F to construct a "synthetic dollar interest rate." In the absence of arbitrage, this synthetic rate must equal the dollar interest rate $i_{\$}$.

We measure covered interest parity deviations with the expression

$$CIPD = i_{\$} - \frac{1}{n}(log(F) - log(S)) - i_f.$$

This expression is positive when dollar interest rates are higher than synthetic dollar interest rates and negative when dollar interest rates are lower than synthetic dollar interest rates. If a global demand for dollar safe assets pushes risk-free dollar rates below synthetic dollar rates constructed from foreign assets, we would observe a negative CIP deviation. Because there are several choices of risk free rates in each currency, CIP deviations can be constructed separately for each class of risk free rate. We refer to $CIPD_{gov}$ as the CIP deviation constructed using US and foreign Treasury yields and $CIPD_{box}$ as the CIP deviation constructed using option-implied box rates from both currencies.

Two previous results in work on CIP deviations are closely related to our results. First, as shown by Du et al. (2018b) and Du et al. (2018a), the cross-section of CIP deviations between LIBOR rates and between Treasury rates across countries are closely related to the level of interest rates in each country. Australia, which has a high nominal interest rate in its own currency, has a low synthetic dollar interest rate. Conversely, Japan has a low interest rate in its own currency but a high synthetic dollar interest rate. Second, these same papers show that the overall level of CIP deviations is negative when averaged across countries. With the exception of extreme cases like Australia, countries tend to have synthetic dollar interest rates that are higher than dollar interest rates in the US. This low interest rate in the US is one crucal piece of evidence that there is a demand for safe dollar assets, likely related to the central role of the US and the dollar in particular in the global financial system.

Using our new estimates of international convenience yields, we can analyze the extent to which the convenience yields explain the magnitudes of CIP deviations across countries.

We decompose the covered interest parity deviation for government debt as

$$CIPD_{gov} = i_{\$,gov} - \frac{1}{n}(log(F) - log(S)) + i_{f,gov} \tag{13}$$

$$= \left(i_{\$,box} - \frac{1}{n}(log(F) - log(S)) + i_{f,box} \right) + [(i_{f,box} - i_{f,gov}) - (i_{\$,box} - i_{\$,gov})] \tag{14}$$

$$= CIPD_{box} + (CY_f - CY_\$). \tag{15}$$

The first term, $CIPD_{box}$ is inferred only from forward and spot currency exchange rates and from the prices of index options in each country. In particular box rate CIP deviations do not directly depend on the yields of any safe assets such as government debt. The second term, $(CY_f - CY_\$)$ is the difference between the convenience yields we estimate in the foreign country and for the US using our box rates. These convenience yields are estimated only from assets within each country and do not depend on exchange rates. This decomposition allows us to separate observed CIP deviations for government debt into two channels. First, the box CIP deviation reflects a spread between dollar discount rates implied by a pricing kernel for US risky assets and a pricing kernel for foreign risky assets. Second, the difference in convenience yields $(CY_f - CY_\$)$ reflects the difference in how much return investors are willing to forgo to hold a safe asset denominated in foreign currency versus one denominated in dollars. Tables 4 and 5 present summary statistics on average CIP deviations for box

Table 4

Summary statistics. Average Box CIP Deviations

Country	3 Month	6 Month	1 Year	2 Year
Australia	0.0000 (.0011)	0.0002 (.0010)	-0.0010 (.0008)	
Canada	-0.0020 (.0010)	-0.0013	-0.0011 (.0002)	-0.0001
Switzerland	-0.0009 (.0003)	-0.0012	-0.0014	-0.0022
Euro	-0.0005 (.0003)	-0.0006	-0.0008	-0.0012
UK	0.0011 (.0005)	0.0002	-0.0004	
Japan	0.0009 (.0014)	.0004 (.0017)	-.0011 (.0018)	
Norway	-0.0012 (.0005)	-0.0011 (.0006)		
Sweden	-0.0014 (.0005)	-0.0023 (.0006)		

rates and government bond yields. For both box and government rates, most CIP deviations are negative, which implies that investors accept a lower rate of return when holding dollar assets than when using the FX market to manufacture synthetic dollar assets from foreign interest rates. However, box and government CIP deviations behave differently when we examine them across countries. In high-interest rate countries like Australia, government CIP deviations are positive, while in low interest rate countries like Switzerland and Japan, government CIP deviations are negative and the largest in magnitude, roughly -40 basis points. As we show visually in figure 5, we replicate the finding in previous work that the size of government CIP deviations is closely related to the level of a country's nominal interest rates. However, this pattern does not exist for box CIP deviations. For example, Australia and Japan have average box CIP deviations that are quite close to each other (for example, a 1 year CIP deviation of -10 basis points for Australia and -11 basis points for Japan). Figure 6 shows that the cross-section of box CIP deviation magnitudes is not closely related to the level of interest rates and also varies quite a bit less across countries. Of particular interest, all box CIP deviation in this figure are negative, reflecting a lower risk-free dollar discount rate implicit in US risky assets than any synthetic risk-free dollar rate that can be constructed from foreign risky assets.

Table 5

Summary statistics. Average Gov CIP Deviations. Standard Errors in Parentheses.

Country	3 Month	6 Month	1 Year	2 Year
Aulstralia	0.0007 (.0004)	0.0004 (.0004)	0.0007 (.0004)	
Canada	0.0002 (.0002)	-0.0003 (.0001)	-0.0006 (.0001)	0.0001 (.0004)
Switzerland			-0.0047 (.0004)	-0.0037 (.0005)
Euro	-0.0012 (.0002)	-0.0014 (.0002)	-0.0018 (.0003)	-0.0022 (.0005)
UK	-0.0019 (.0005)	-0.0013 (.0003)	-0.0006 (.0002)	-0.0001 (.00005)
Japan	-0.0032 (.0003)	-0.0036 (.0003)	-0.0044 (.0003)	
Norway	-0.0002 (.0003)	-0.0006 (.0004)		
Sweden	-0.0010 (.0005)	-0.0011 (.0004)		

Based on these findings, we conclude the average level of government CIP deviations is not explained by levels of convenience yields, although the cross section of government CIP deviations is. Across countries, the strong relationship between the size of CIP deviations and the level of interest rates is explained by the fact that interest rates also are closely related to the size of convenience yields. In equation 15, the convenience yield difference term $CY_f - CY_\$$ is the main force that drives the variation of $CIPD_{gov}$ across countries. The overall level of government CIP deviations, however, which averages -15 basis points for the data points in figure 5 is driven primarily by the average box CIP deviation of -10 basis points for the data points in figure 6. As explained in section C, the US convenience yield is not unusually large compared to other countries, so the size of the average government CIP deviation gets only a small contribution from the cross-country mean of the convenience yield difference $CY_f - CY_\$$ in equation 15. Our results are related to evidence presented by Du et al. (2018b) that CIP deviations are related to bank regulation.[5] They show that the LIBOR CIP deviations they study 1. were very small before regulatory changes that followed the 2008 financial crisis and 2. increase in magnitude at the end of quarters, when European banks are under the most regulatory scrutiny. Based on these two findings, they argue that CIP deviations are not arbitraged away because banks face a regulatory cost from performing arbitrage trades. However, Wallen (2020) points out that CIP deviations vary significantly in size across countries, even though the bank regulations he considers should impose an equal regulatory cost on a CIP trade regardless of the currency involved. Our finding that box CIP deviations are roughly similar in size across countries suggests that asset prices are fairly consistent with banks facing a regulatory cost of arbitrage trades that is not currency specific. Under this interpretation, the cross-sectional dispersion in the size LIBOR and Treasury CIP deviations can be interpreted as reflecting differences in convenience yields offered by bank debt and government debt denominated in different currencies.

[5] See also Boyarchenko et al. (2020) providing evidence that relates bank regulation to a broader range of arbitrage spreads.

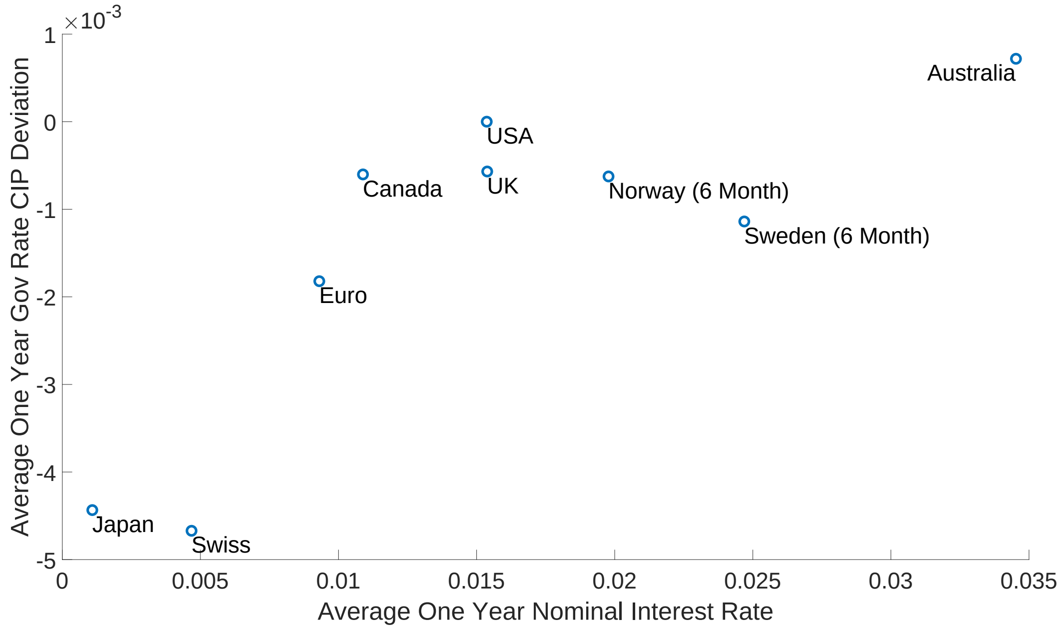

Figure 5. Cross-Section of Nominal Interest Rates and Government CIP Deviations

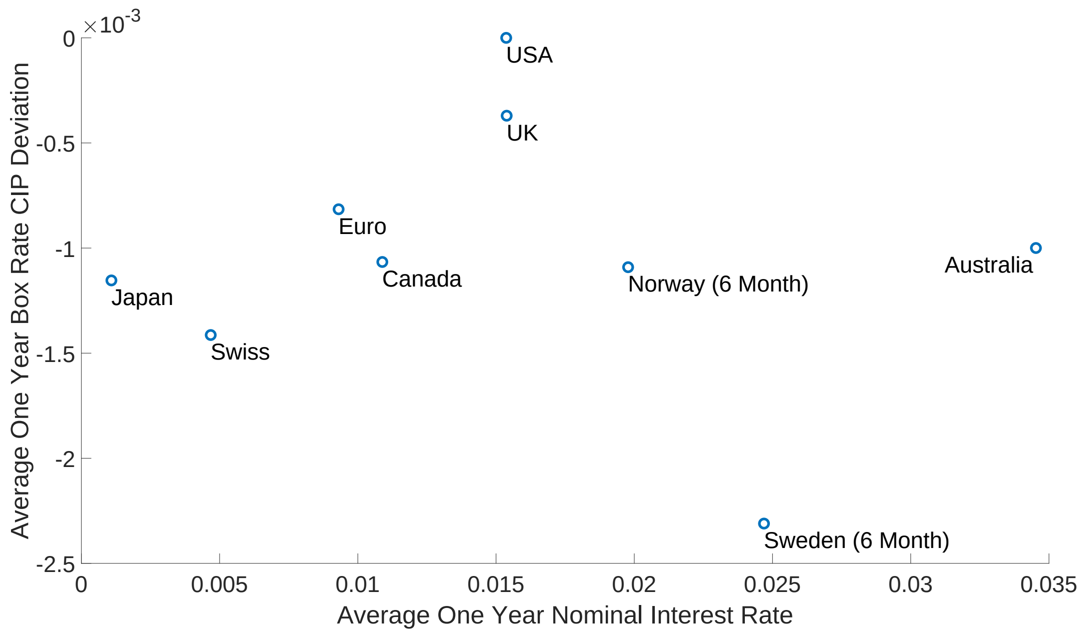

Figure 6. Cross-Section of Nominal Interest Rates and Box CIP Deviations

E Convenience Yields Around The World: Time Series Evidence

This section examines the behavior of convenience yields over time. We first present a time series of one year convenience yields in figure 7 for the four currencies with the

Table 6. Cross Country Regressions of Government CIP Deviations and Box CIP Deviations on Average Treasury Rates, 1-Year Maturity

Coefficient	Gov CIP Deviation	Box CIP Deviation
Intercept	-0.0036581 (0.00075)	-0.00090232 (0.00042)
Slope	0.14575 (0.042033)	-0.0081078 (0.02356)
R-squared	0.632	0.0166

most precise rate estimates, the US, UK, Euro, and Switzerland. These convenience yields co-move strongly with each other and seem to rise during identifiable periods of financial distress. Figures 8 and 9 present time series results for the remaining currencies, which have more volatile fluctuations. For our most precisely estimated currencies, the US and Euro, we present plots of the term structure of their convenience yields in figures 10 and 11.

Although the US does not have an unusually large convenience yield, it is unique in how much its financial crises impact convenience yields around the world. In figure 7, all countries have by far their largest convenience yields following the 2008 financial crisis. While the US convenience yield reaches the highest level at roughly 120 basis points, the UK and Switzerland both exceed 100 basis points, and the Euro exceeds 80 basis points.

The European financial crisis in 2011-2012 leads to a relatively large Euro convenience yield breaking 60 basis points, but this event has only moderate spillovers onto other currencies. In addition, the UK convenience yield exceeds 60 basis points following the June 23 2016 Brexit vote, but convenience yields in other currencies do not spike in a similar manner. After the Swiss broke their currency peg with the Euro on Jan 15 2015 and pushed their rates to deeply negative territory, their convenience yields stay quite negative for the rest of the sample. Swiss convenience yields in particular seem immune to spillovers from financial distress in other countries after 2008.

Figure 4 plots a time series of 3 month convenience yields in Sweden, Canada, and Norway, the countries with the next most liquid option markets. Sweden, which is the most liquid of the 3 has a uniquely large spike in its convenience yield above 250 basis points in the 2008 financial crisis. It also has a relatively high convenience yield in the 2011-2012 Euro

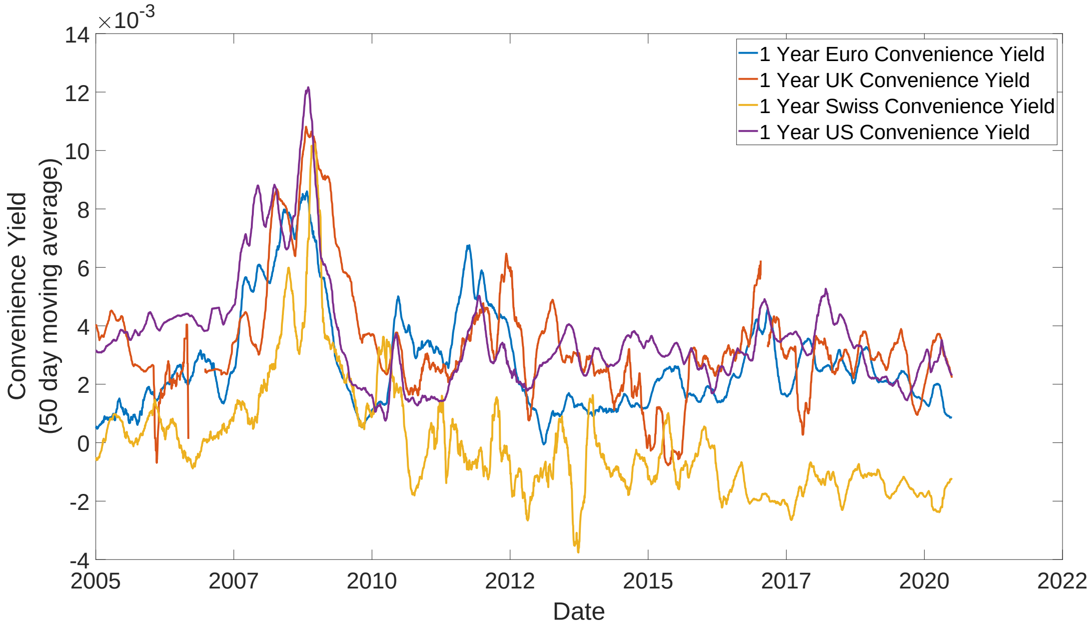

Figure 7. One-Year Convenience Yields, Measured as One-Year Box Rates Minus One-Year Government Yields, for the US, UK, Euro, and Switzerland.

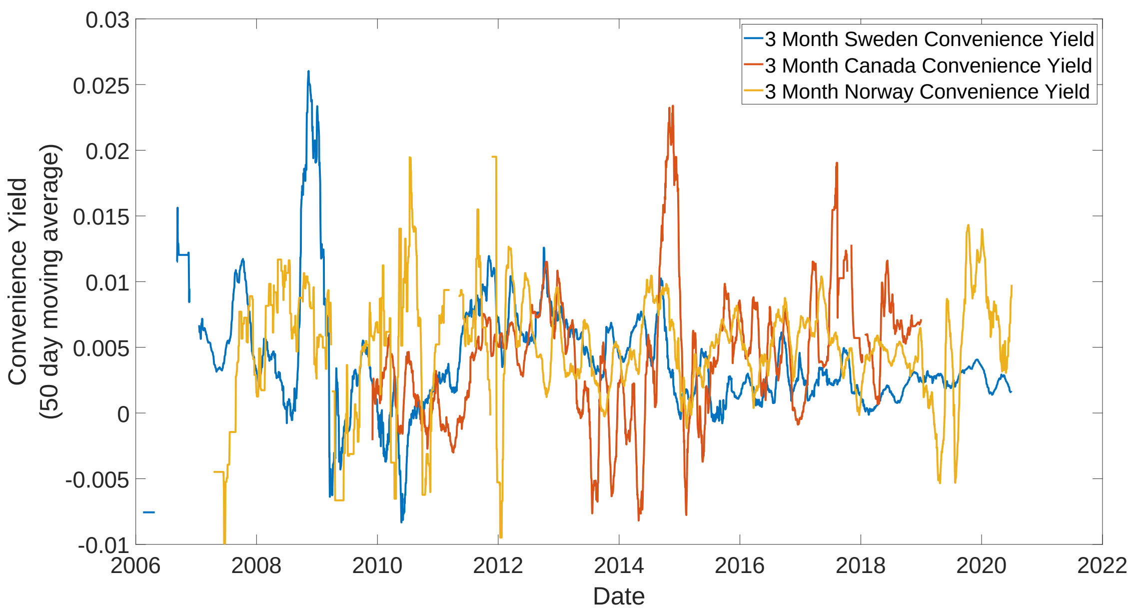

Figure 8. Three-Month Convenience Yields, Measured as One-Year Box Rates Minus One-Year Government Yields, for Sweden, Norway, and Canada.

crisis. Canada and Norway, and to a lesser extent Sweden, have large fluctuations in their convenience yield estimates that do not seem directly related to particular macroeconomic

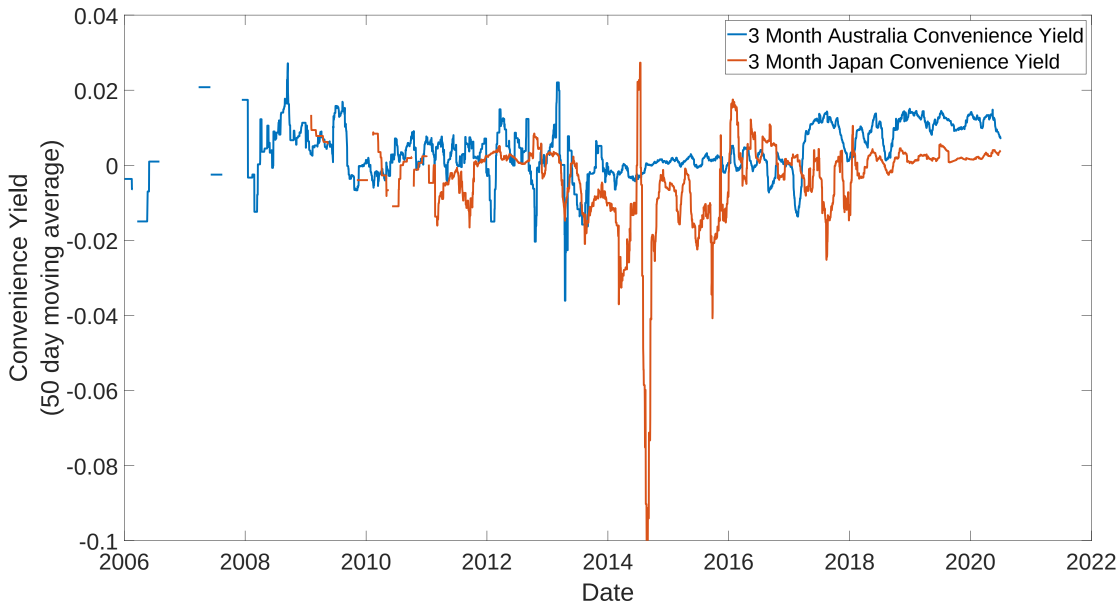

Figure 9. Three-Month Convenience Yields, Measured as One-Year Box Rates Minus One-Year Government Yields, for Australia and Japan.

events and do not spill over to other countries. With the partial exception of Sweden, the time series variation in these currencies are less connected to macroeconomic events than in the 4 plotted above. Figure 5 plots 3 month convenience yield estimates for the least liquid 2 currencies, Australia and Japan. The fluctuations in these convenience yield estimates are even more dramatic than for the 3 currencies in figure 4 and also do not seem to have a clear relationship with specific macroeconomic events. Nevertheless, Australian convenience yields are nearly always above those of Japan, suggesting that the differences in their sample averages are not an artifact of statistical noise.

Term Structure of Convenience Yields

Figures 5 and 6 present time series plots of the term structure of convenience yields for the two most liquid markets, the Euro and the US. In both countries, there is a strong co-movement of convenience yields across maturities, with all maturities moving up together in the 2008 and 2011-2012 Us and Euro financial crises. Smaller convenience yield movements than these two crises also seem to be strongly correlated across maturities in each country. Nevertheless, the two term structures differ markedly in their conditional slope. In Europe, periods of financial distress feature particularly high convenience yields for the shortest maturities, with longer maturity convenience yields increases too but less so. In the US , the term structure of convenience yields remains nearly flat even when it is elevated.

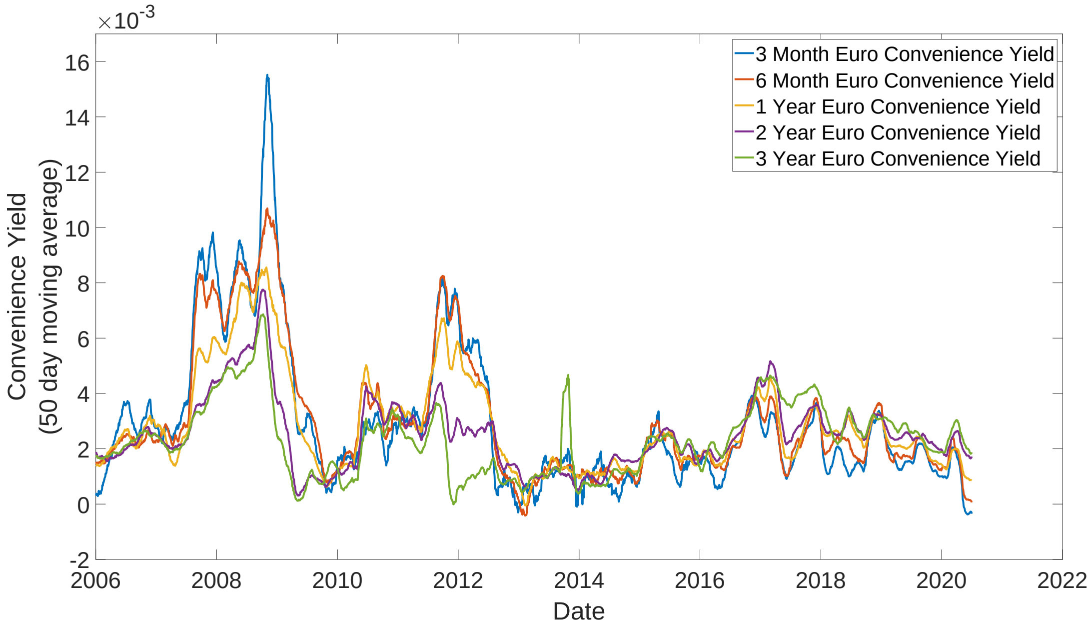

Figure 10. Term Structure of Euro Convenience Yields Over Time

F Covered Interest Parity Deviations over Time

This section analyzes the time series behavior of Box and Government CIP deviations to understand how dollar safe assets behave during periods of financial crisis. Because the US, Europe, the UK, and Switzerland have the most precisely estimated option-implied interest rates, we restrict ourselves to analyze only these countries in this section. As previous literature has documented (Du et al., 2018a), government CIP deviations grow dramatically during periods of financial crisis such as 2008-2009. By decomposing government CIP deviations into box CIP deviations and convenience yield differences using equation 15, this section aims to understand whether a special demand for dollar-denominated safe assets is

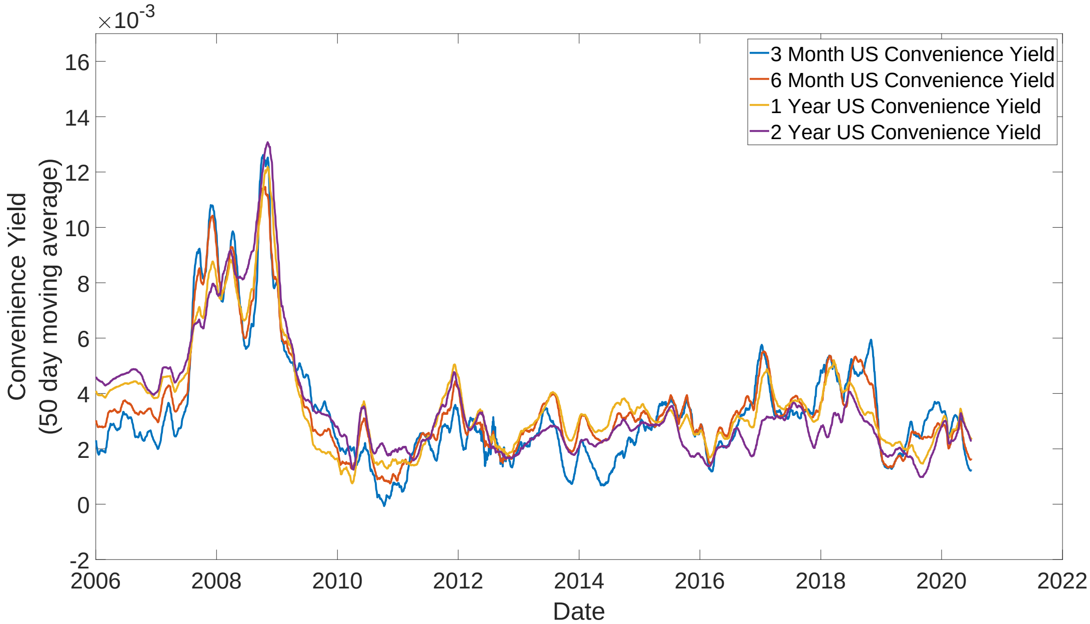

Figure 11. Term Structure of US Convenience Yields Over Time

a key feature of financial crises. We study the behavior of two time series: 1.the average one-year box CIP deviation between of the UK, Europe and Switzerland and the US and 2. the difference between the average one-year convenience yield of the UK, Europe and Switzerland and the US one-year convenience yield.

We find that box CIP deviations become large and negative during financial crises. In the 2008-2009 US financial crisis, the 2011-2012 European financial crisis, and the financial turmoil surrounding Brexit in June, US box rates fall below synthetic dollar interest rates constructed using foreign box rates and currency hedging. However, during tranquil periods in financial markets (i.e. when convenience yields are low in figure 7), synthetic dollar box rates return back to or slightly above the level of US box rates. This is reflected in the blue line in figure 12.

However, the difference between US and foreign convenience yields does not seem to grow on average during periods of financial turmoil. While we do see an increase in this convenience yield difference in 2008 following the bankruptcy of Lehman brothers, it reaches a level that was fairly average in the pre-2008 part of the sample of just below 40 basis points.

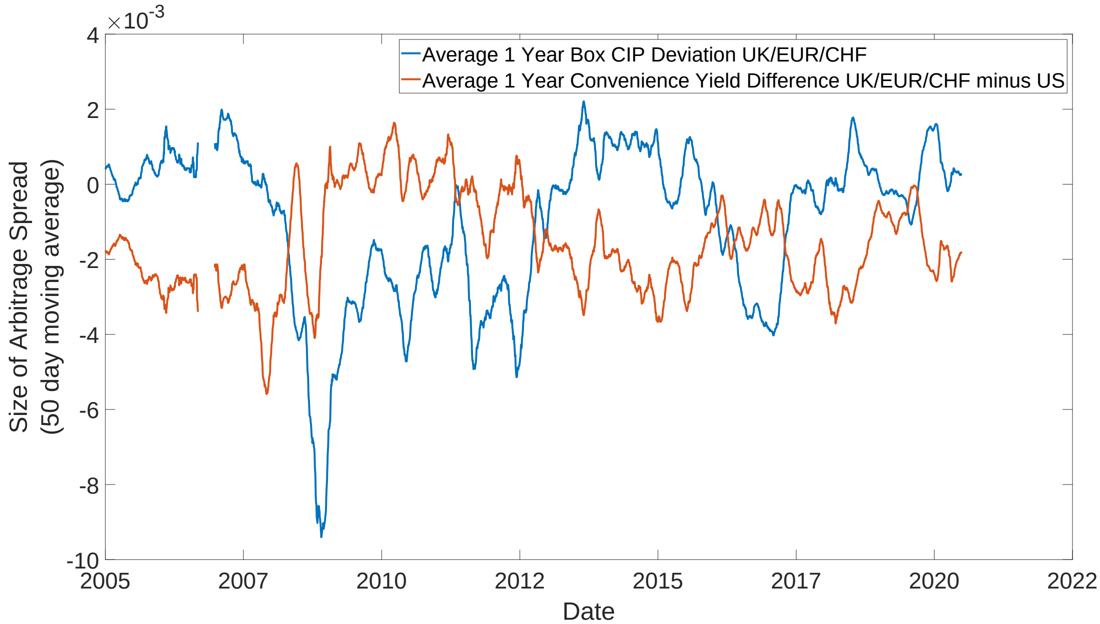

Figure 12. Box CIP deviations and Convenience Yield Differences Over Time

During the European financial crisis and after Brexit, we in fact see foreign convenience yields growing relative to US convenience yields. While we only have a few crisis events in our sample, this suggests that US convenience yields should only be unusually large during financial crises centered on the US This is in contrast to the box CIP deviations which become increasingly negative during all financial crises we observe. The correlation between these two series is -.56. Because the sum of these two series (as implied by equation 15) equals the government CIP deviation averaged across these currencies, this negative correlation implies that convenience yield differences tend to reduce rather than amplify the size of government CIP deviations during financial crises. Table **??** provides addition support for this. The average level of government CIP deviations predicts the average level of box CIP deviations with a slope coefficient of .86 and and R-squared above .5, while its predictive power for the level of convenience yield differences is minimal.

Table 7

	Box CIP	Conv. Yield Difference
Intercept	0.0011565 (.00005)	-0.0011565 (.00005)
Slope	0.86022 (0.014129)	.13978 (.014129)
R-squared	.509	.0266

Regressions of box CIP Deviations and Convenience Yield Differences on government CIP Deviations. The first column presents time series regression results of the average one-year box CIP deviation for the UK Europe and Switzerland on the average one-year government CIP deviation for these same three countries. The second column presents time series regression results of the difference in the average one-year convenience yield of these 3 countries on the average of their one-year government yield CIP deviations. Observations are at a daily frequency.

G Convenience Yields and CIP Deviations in the 2020 Covid Crisis

This section analyzes the behavior of CIP deviations and convenience yields during the brief period of financial turmoil in March 2020 that occured with the advent of COVID-19 in the US. The short period of turmoil in March 2020 is not easily visible in the charts above, since a 50 day moving average nearly removes the event. As documented in He et al. (2021), Ma et al. (2021), this crisis differed from others in that there was selling pressure in the US Treasury market, with some long term Treasury rates increasing. At the maturities for which we have box rates, we show in figure 13 that Treasury convenience yields temporarily became negative in this period, consistent with the idea that Treasuries faced unusual selling pressure.

However, we also show in figure 14 that box CIP deviations behaved similarly in this crisis as in previous ones. Across all maturities from 6 months to 2 years[6] for the UK, Euro, and Switzerland, synthetic dollar box rates were well above actual dollar box rates, with the difference peaking near 60 basis points for many assets. This is consistent with our previous finding- in all observed financial crises, dollar box rates fall below synthetic dollar box rates

[6] We find similar results at a 3 month maturity, though the magnitudes are so big as to be difficult to plot in a single figure.

constructed from FX forwards and foreign option prices. As shown in figure 15, dollar convenience yields were low relative to those of other countries, suggesting that the turmoil in the US Treasury market was not seen in other countries. Although a negative dollar convenience yield is unusual, the opposite movement of box CIP deviations and convenience yields across countries is consistent with the overall time series pattern shown above in figure 12. However, the relative magnitudes are somewhat unusual. While the drop in box CIP deviations during a crisis tends to result in a fall in government CIP deviations too, here the fall in dollar convenience yields was large enough to result in synthetic dollar government yields falling below actual Treasury yields. This is reflected in the temporary positive government CIP deviation in figure 15 in March 2020.

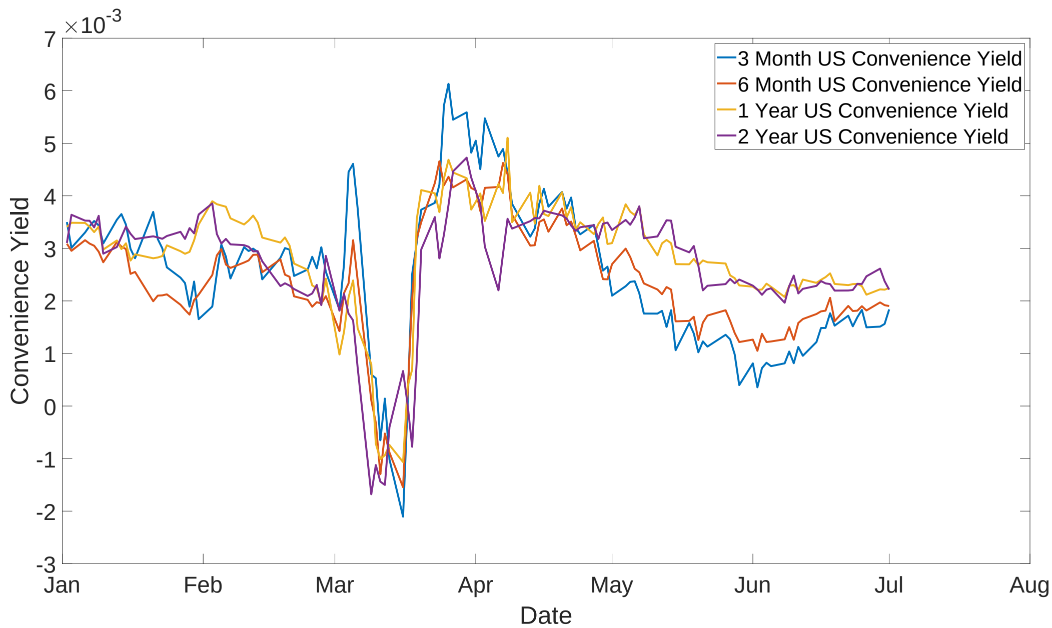

Figure 13. US Convenience Yields during 2020 Covid Crisis

H Precision of Rates Over Time

Our final analysis studies the time series behavior of the R-squareds of the put-call parity regressions we use to estimate our interest rates. In figure 16, we plot a weighted average of

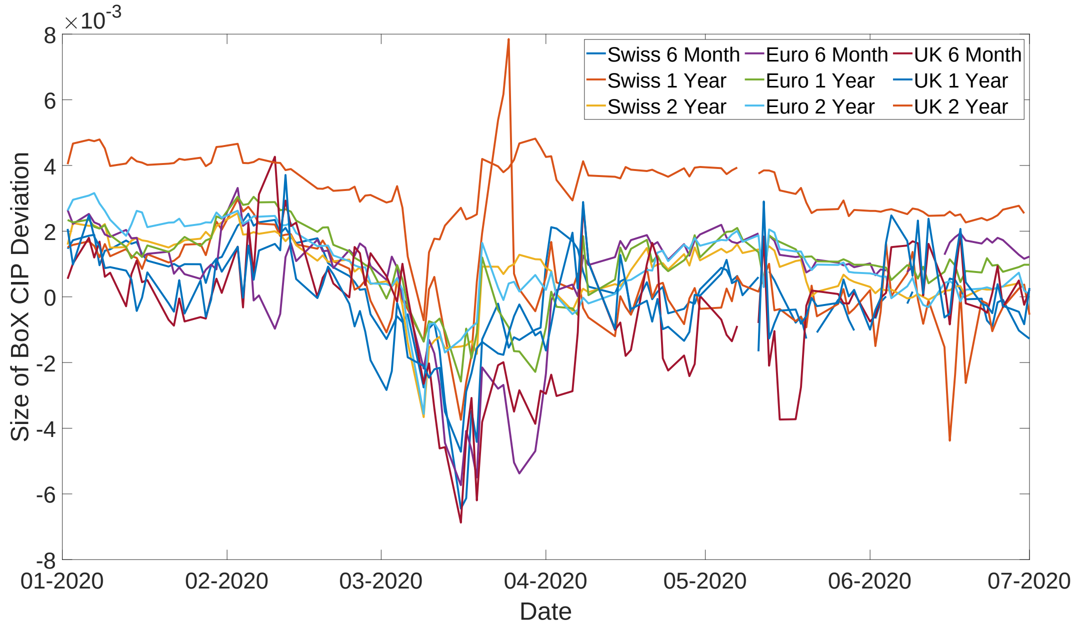

Figure 14. Box CIP Deviations During 2020 Covid Crisis

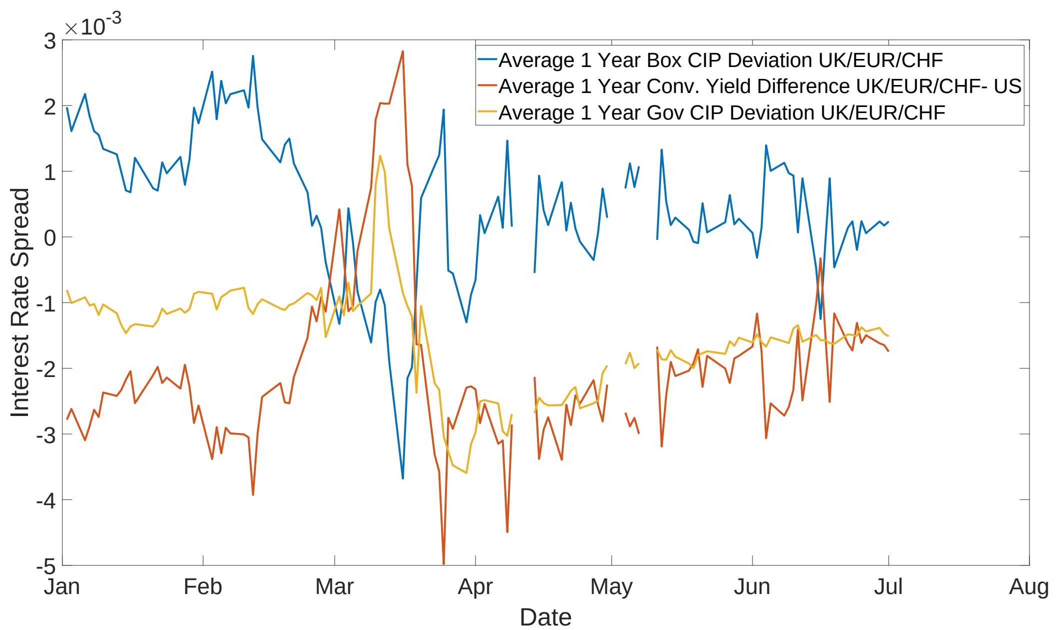

Figure 15. Average Box CIP, Convenience Yield Differences, and Government CIP Deviations During 2020 Covid Crisis

the R-squareds of all currencies except that of Australia[7], with the weights determined by constructing the first principal component of the R-square time series and then normalized

[7]Because Australia's rates are the most volatile, a principal component would put large weight on this single currency.

to sum to one. This time series drops significantly in the 2008 financial crisis, 2011 European debt crisis, and modestly after Brexit and in March 2020. In addition, the series trends up over time, reflecting the fact that options markets are becoming more liquid. To compare

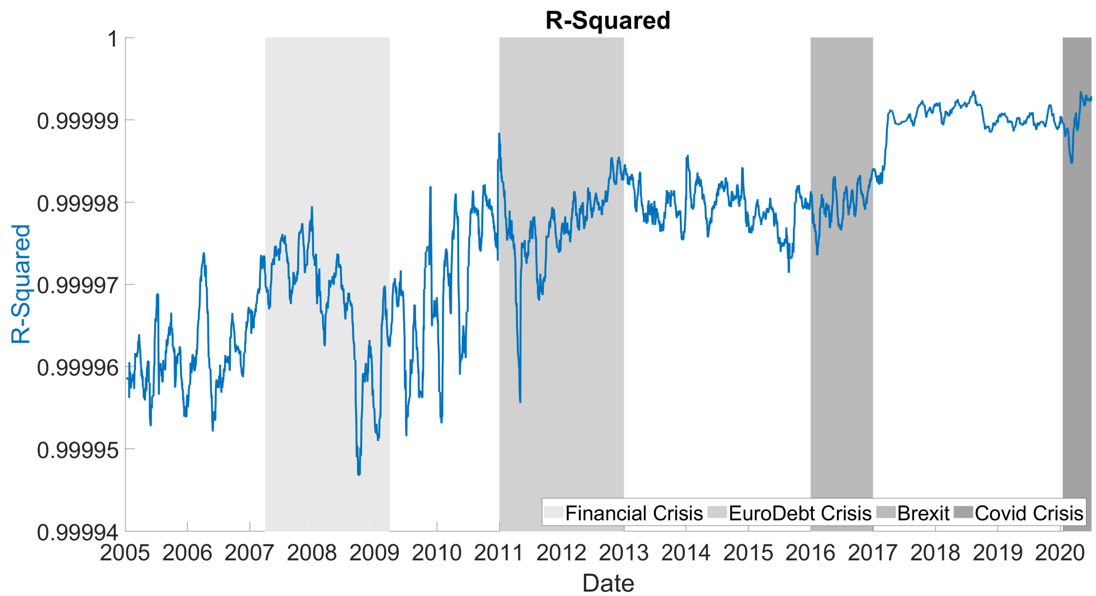

Figure 16. Time series of the first principal component of normalized R-squareds of put-call parity regressions. For each currency and each day, we take the average R-squared of our put-call parity regression across different maturities of the subset of R-squareds above .9999. The chart plots a weighted average of R-squared across all currencies except Australia, where the weights are those that yield the first principal component of the R-squared (normalized to sum to one).

the magnitudes of various financial crises with this trend removed, figure 17 plots a weighted average (again with the weights determined by forming the first principal component) of a normalized R-squared measure. This measure for each currency is $\frac{1-MU(R^2,10)}{1-MU(R^2,252)}$, where $MU(R^2,d)$ is the d-day moving average of the currency's daily R-squared. This measure has an interpretation of how far a currency's R-squared is away from one at a given time divided by an average of this distance over a somewhat longer time window. Under this normalized measure, the spike in option market illiquidity during the covid crisis is unprecedented. R-squareds in March 2020 were over four times as far as way from one as they were in the 252 day window around the crisis event. This shows that option market illiquidity and large increases in convenience yields, although they both tend to happen during financial crises, are not driven by exactly the same forces. One potential explanation is that because

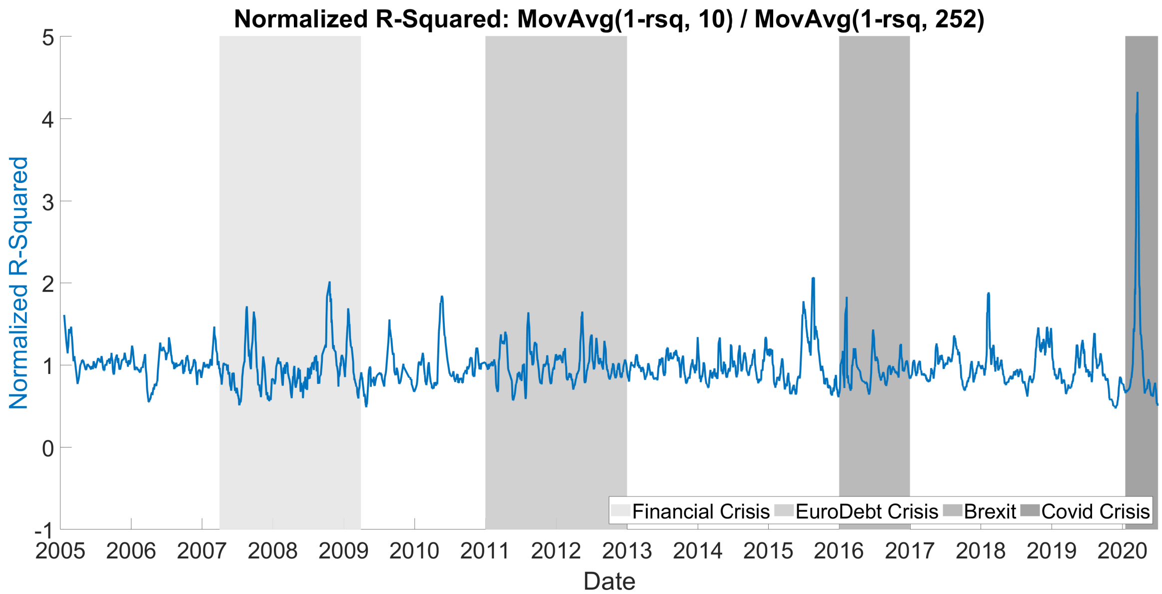

Figure 17. Time series of the first principal component of normalized R-squareds of put-call parity regressions. For each currency and each day, we take the average R-squared of our put-call parity regression across different maturities of the subset of R-squareds above .9999. We then compute the ratio of a 10 day moving average of one minus this R-squared to a 252 day average of one minus this r-squared to create a "normalized R-squared." The chart plots a weighted average of normalized R-squared across all currencies except Australia, where the weights are those that yield the first principal component of the R-squared (normalized to sum to one).

convenience yields are the rate of return investors are willing to forgo in order to hold a safe asset, they spike when the banking system (who creates safe assets such as bank deposits) in particular is in trouble. Because 2008 and the 2011-2012 European debt crisis pushed banks near insolvency, while the covid crisis did not, it makes sense that convenience yields are large particularly in 2008 and 2011-2012. The covid crisis however, as shown by He et al. (2021), Ma et al. (2021), featured selling pressure from non-bank investors that impacted asset prices. Because our option data can be used to construct both a convenience yield and an R-squared measure that are impacted by different frictions, they are quite useful for distinguishing different types of financial crises.

I Conclusion

This paper constructs option-implied interest rates for 9 of the 10 G10 currencies and used them to quantify the convenience yield of safe assets in each currency. We find that the US convenience yield of 34 basis points is fairly average, and the cross section of countries' convenience yields is explained well by the level of interest rates in each country. This cross-sectional pattern also explains why the level of government debt CIP deviations across countries is strongly related to the level of each country's interest rates. However, CIP deviations constructed from our option-implied box rates are negative for all countries, suggesting that it is a demand for US assets in general and not specifically for US government debt that is uniquely large. Over time, box CIP deviations grow substantially in crises, but US convenience yields grow no more than those in other currencies. Overall, we find that US assets can pay uniquely low yields, likely due to the US's central position in the global financial system, but that the convenience yield earned by US safe assets is not uniquely large in addition. In future work, we hope to use our international box rate estimates to analyze the impact of central bank policy interventions and to understand what role our convenience yield estimates play in determining currency exchange rates.

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