

Diamond, William; Van Tassel, Peter

Working Paper

Risk-free rates and convenience yields around the world

Staff Report, No. 1032

Provided in Cooperation with:

Federal Reserve Bank of New York

Suggested Citation: Diamond, William; Van Tassel, Peter (2022) : Risk-free rates and convenience yields around the world, Staff Report, No. 1032, Federal Reserve Bank of New York, New York, NY

This Version is available at:

<https://hdl.handle.net/10419/266116>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

NO. 1032
SEPTEMBER 2022

Risk-Free Rates and Convenience Yields Around the World

William Diamond | Peter Van Tassel

Risk-Free Rates and Convenience Yields Around the World

William Diamond and Peter Van Tassel

Federal Reserve Bank of New York Staff Reports, no. 1032

September 2022

JEL classification: G12, G15, C58

Abstract

This paper constructs risk-free interest rates implicit in index option prices for ten of the major G11 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 2 basis points in low-rate Switzerland to 61 basis points in high-rate Australia, with the moderate-rate United States 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 United States 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 United States are especially low due to its central position in the global financial system, particularly during financial crises, but that U.S. safe assets do not earn an unusually large convenience yield in addition.

Key words: risk-free rates, convenience yields, covered interest rate parity, options

Van Tassel: Federal Reserve Bank of New York (email: peter.vantassel@ny.frb.org). Diamond: Wharton School, University of Pennsylvania (email: diamondw@wharton.upenn.edu). The authors thank Max Yang for outstanding research assistance, Jesse Schreger, Jonathan Wallen, and Zhengyang Jiang for comments, and Alyssa Anderson for a very helpful conference discussion. They also thank the Wharton Dean's Research Fund, Jacobs Levy Equity Management Center, and Rodney White Center for Financial Research for generous financial support.

This paper presents preliminary findings and is being distributed to economists and other interested readers solely to stimulate discussion and elicit comments. The views expressed in this paper are those of the author(s) and do not necessarily reflect the position of the Federal Reserve Bank of New York or the Federal Reserve System. Any errors or omissions are the responsibility of the author(s).

To view the authors' disclosure statements, visit
https://www.newyorkfed.org/research/staff_reports/sr1032.html.

I Introduction

In developed economies with a minimal risk of sovereign default, government debt is a uniquely safe and liquid financial asset which plays a role similar to money. In particular, 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. Recent empirical work (Krishnamurthy and Vissing-Jorgensen, 2012, Nagel, 2016, van Binsbergen et al., 2021) documents that because of this special safety and liquidity, government debt in the US earns a so-called “convenience yield,” a non-pecuniary value of holding government debt (or a similar safe, money-like asset) that raise its price above the present value of the future cash flows it pays.

This paper provides empirical estimates of the convenience yield of government debt denominated in 10 of the G11 currencies. 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 database of intraday time-stamped option price quotes on the main stock index in each country from 2004 to 2020. Exploiting the put-call parity relationship for European options, 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 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 size of a country’s average convenience yield is highly correlated with the level of interest rates in that country. High nominal rate currencies such as Australia, Norway, and Sweden have the largest average convenience yields of up to 60 basis points, while low rate

currencies Switzerland, Denmark, and Japan have average convenience yields as low as 2 basis points. A cross-sectional regression of a country's the average convenience yield on its average one year government bond yield fits with an R-squared of .844, with a 1 percent higher rate predicting a 15 basis point higher convenience yield. However, when a country's nominal interest rate is negative, the size of its negative interest rate is nearly uncorrelated with the magnitude of the convenience yield. The residual for the US in this regression is only 1.4 basis points, with an average convenience yield of 35 basis points and average level of interest rates that are roughly in the middle of the 11 countries we analyze. This implies that despite its central role in the global financial system, the US does not earn an unusually large convenience yield on its government debt.

We use our risk-free box rate estimates to construct covered interest parity (CIP) deviations free from the influence of safe asset convenience yields. CIP is a no-arbitrage relationship that states that a foreign risk-free rate swapped into a synthetic dollar risk-free rate using currency derivatives should equal the dollar risk-free rate. A literature going back to Du et al. (2018b) shows that particularly since the 2008 financial crisis, CIP deviations are a persistent feature of the data. For CIP deviations constructed from government debt yields or interbank borrowing rates such as LIBOR, dollar rates tend to be lower than synthetic dollar rates swapped from foreign currency. In addition, the cross-section of countries' CIP deviations are strongly related to the country's level of interest rates.

For our box rates, every synthetic dollar rate constructed with a non-US country's box rate is strictly higher than the US box rate on average, and there is remarkably little variation in the size of the average "box CIP deviation" across countries. Most countries have an average box CIP deviation close to an average of 11 basis points. If we have accurately estimated the level of convenience yields in each country, this implies that variation in the level of CIP deviations across non-US countries is almost entirely due to the level of convenience yields in each country. Closest to our result is Liao (2020), who finds that CIP deviations constructed from risky corporate bond yields are also fairly constant across

countries, though our use of risk-free rates clarifies that safe asset convenience yields rather than differential pricing of credit risk explains our finding.

We rationalize our cross-sectional empirical findings in a simple theoretical model. In the model, consumers obtain a reduced-form “liquidity benefit” from holding an aggregate of cash and bank deposits. When interest rates are positive, the liquidity provided by cash and deposits are closely substitutable. Because earning interest is the opportunity cost of holding cash, the nominal interest rate must be equal the convenience yield of holding cash, which implies (as noted by Nagel (2016)) that the level of interest rates determines the magnitude of convenience yields on non-cash assets. When interest rates are negative, the hassle of storing large quantities of a physical asset such as cash is not shared by deposits or other electronic assets, so the relationship between interest rates and convenience yields breaks down.

Bank deposits are created in the model by financial intermediaries who face regulatory capital constraints. Holding safe assets such as Treasuries relaxes this regulatory requirement and allows the intermediary to issue more deposits. Deposit interest rates are a cheap form of financing when deposit convenience yields are large, and this boosts the intermediary’s willingness to pay for Treasuries, resulting in a larger Treasury convenience yield. As a result, Treasury convenience yields (or convenience yields on other safe assets held by financial institutions) are also increasing in the level of interest rates when rates are positive. In addition, there is an international dealer bank/ hedge fund that arbitrages across countries and also faces a regulatory capital constraint. If the regulatory cost of doing arbitrage trades is the same regardless of which foreign country is on the other side of the trade, interest rate spreads like our box CIP deviation should be equalized across countries. If the US hedge fund/dealer bank sector is a net lender in foreign countries, our model replicates our finding that every country has a nonzero CIP deviation with the dollar and that these CIP deviations are roughly constant across countries.

We conclude by examining the time series behavior of convenience yields and box CIP

deviations. During financial crises, we find that safe asset convenience yields tend to grow, but not disproportionately in the US relative to other countries. The 2008-2009 financial crisis has a disproportionate growth in US convenience yields, while the 2011-2012 Euro crisis has European convenience yields growing the most, and the 2016 Brexit crisis leads primarily to growth in UK convenience yields. However, in all financial crises regardless of the country of origin, we find that box CIP deviations move in the same direction, with US box rates falling below synthetic dollar yields constructed from foreign box rates. Box CIP deviations reach a peak of 80 basis points in the 2008 crisis and values of roughly 40 basis points in other crises. In non-crisis periods such as before 2008, from 2013-2015, and after the 2016 Brexit crises, box CIP deviations are extremely close to 0, consistent with our theoretical interpretation that box CIP deviations are due to frictions in international financial arbitrage.

Box CIP deviations have a strong relationship with exchange rates in the time series. This builds on Engel and Wu (2022), who show that government CIP deviations are strong predictors of exchange rates. We decompose each country's government debt CIP deviation into a box CIP deviation (which we argue is a measure of international financial frictions) and the difference between that country's convenience yield and the convenience yield in the US. We show that both the box CIP deviation term and the convenience yield difference term are useful for forecasting movements in the country's exchange rate at a monthly frequency, with a 100 basis point increase in each respectively predicting a 5 % and 4 % depreciation in the country's currency relative to the dollar.

Following Avdjiev et al. (2019)'s analysis of LIBOR CIP deviations, we also show that a country's box CIP deviation tends to grow in magnitude when the dollar strengthens, and that the dollar's return against a broad basket of other currencies is a much stronger predictor of box CIP deviations than the dollar's return against the country's own currency. However, we do not find that the difference between a country's convenience yield and that of the US co-moves strongly with either dollar exchange rate. Because the dollar tends

to appreciate during periods of financial distress, this adds to the evidence that box CIP deviations tend to be large during global financial crises but that US convenience yields do not grow disproportionately during crises compared to convenience yields in other countries.

We conclude with three final analyses. First, we confirm using monthly panel data our cross-sectional result that convenience yields are related to the level of nominal interest rates. We confirm also that this relationship breaks down when nominal interest rates are negative, with country fixed effects predicting the level of convenience yields far better than time series variation in interest rates. Second, we examine the short but unique March 2020 Covid-19 financial crisis. We find that US convenience yields became temporarily negative unlike in other countries, likely due to selling pressure in the US Treasury market (He et al., 2021). However, box CIP deviations spike during this crisis similarly to how they behave in other crises. Finally, we examine the time series behavior of microstructure frictions in option markets, measured by the R-squared of the regressions which identify our box rates. These R-squared drop during crises and have an unprecedentedly large drop in the Covid-19 crisis, documenting that microstructure frictions can be severe even when convenience yields are not large.

Our results clarify the ways in which the US is unique in the global financial system. The convenience yields earned on US safe assets that we estimate do not seem to be particularly large or particularly cyclical when compared to those in other countries. However, our box CIP deviation, which is estimated entirely from derivatives prices and not from the yields on safe assets, does behave differently for the US than it does for other countries. US box rates are lower than synthetic dollar rates constructed from foreign options prices, particularly during financial crises, regardless of whether that crisis originated in the US or in other countries. In sum, we find that US financial markets as a whole seem to have uniquely high valuations during periods of financial distress, but that US safe assets in particular do not have an unusually large convenience yield on top of this.

A Near-Money Assets and Convenience Yields

We first explain the intuition behind our approach to estimating the convenience yields of safe assets. Our goal is to compare the yield of a safe, money-like asset to the risk-free rate of return implied by the prices of assets that are not themselves safe or money-like. Generally, the previous literature has approached this problem by using the yield on a less liquid and/or less safe asset for comparison. However, any sufficiently safe asset can itself have a convenience yield, since it can also perform a role similar to money. For example, in the original IS-LM model of Hicks (1937) the nominal interest rate measures the return that agents forgo in exchange for holding cash. However, as shown by Krishnamurthy and Vissing-Jorgensen (2012), a risk-free rate inferred from Treasury yields reflects the fact that Treasuries are also safe assets that provide some degree of convenience. The spread between the yield on Treasuries and the (zero) yield on cash therefore identifies only the difference in convenience yields of the two assets.

Following, van Binsbergen, Diamond, and Grotteria (2021), our approach aims to infer a risk-free rate from assets which are themselves so far from being safe, money-like assets that they are quite unlikely to provide a convenience yield themselves. Figure 1 suggests an approach for estimating convenience yields which is valid if an asset's convenience decreases smoothly in the asset's systematic risk before eventually reaching a level of zero for risky assets outside of the fixed income market. 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). 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. Based on this picture, comparing 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, very low risk assets such as the debt of banks or AAA rated companies have their returns reduced by the fact that

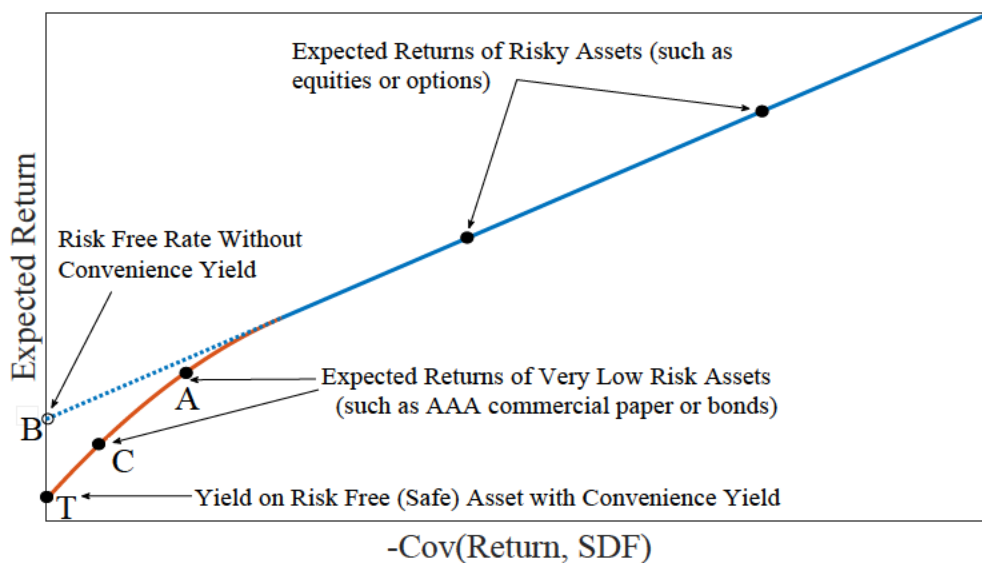


Figure 1. Risk and return with a special demand for safe assets (convenience).

they are somewhat money-like and provide convenience themselves. On the other hand, these low risk assets need 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 or below the convenience-yield-free risk-free rate (as shown by points C and A in Figure 1). 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.

B Constructing risk-free 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 all denominated in the same currency for $i = 1, \dots, N$. We aim to infer the interest rate in this currency $r_{t,T}$ on a riskless investment 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 $p_{i,t,T}$ and $c_{i,t,T}$, the put-call parity relationship can be written

as

$$p_{i,t,T} - c_{i,t,T} = (\mathcal{P}_{t,T} - S_t) + \exp(-r_{t,T}T)K_i. \quad (1)$$

In this expression, S_t is the price of the underlying asset on which the options are written and $\mathcal{P}_{t,T}$ is the present value of cash flows paid by the underlying asset before the options mature. The put-call parity relationship 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 $p_{i,t,T} - c_{i,t,T}$ between the prices of puts and calls of strike price K_i and the strike price K_i . The slope of this line equals the discount factor $\exp(-r_{t,T}T)$ from which we can infer the interest rate $r_{t,T}$. We therefore can estimate our option-implied interest rates from a cross-sectional linear regression of $p_{i,t,T} - c_{i,t,T}$ on K_i . By estimating this regression separately for options whose strike prices are denominated in different currencies, we obtain rate estimates for each currency. These rates are risk-free if there is no meaningful counterparty risk on the options used to construct the rate estimate, a claim for which we provide evidence in appendix C.

We can write our linear put-call parity expression as

$$p_{i,t,T} - c_{i,t,T} = \alpha_{t,T} + \beta_{t,T}K_i + \varepsilon_{i,t,T}. \quad (2)$$

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

$$\beta_{OLS} = \frac{\sum_i ((p_{i,t,T} - c_{i,t,T} - \bar{p} - \bar{c})(K_i - \bar{K}))}{\sum_i (K_i - \bar{K})^2}, \quad (3)$$

where a variable with a bar over it denotes its sample average. Our implied interest rate

estimate is then

$$r_{t,T} = -\frac{1}{T} \ln(\beta_{OLS}). \quad (4)$$

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 will use the R-squared of this regression as a measure of frictions in an option market that result in arbitrage opportunities. This 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 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 -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 when such rates are in our data.

C Convenience Yields Around The World: Cross-Sectional Evidence

This section presents our results on the average size of our convenience yield estimates in G11 countries with two main results. First, the convenience yield we estimate for the US bonds is roughly the average convenience yield across the G11 countries at 35 basis points.

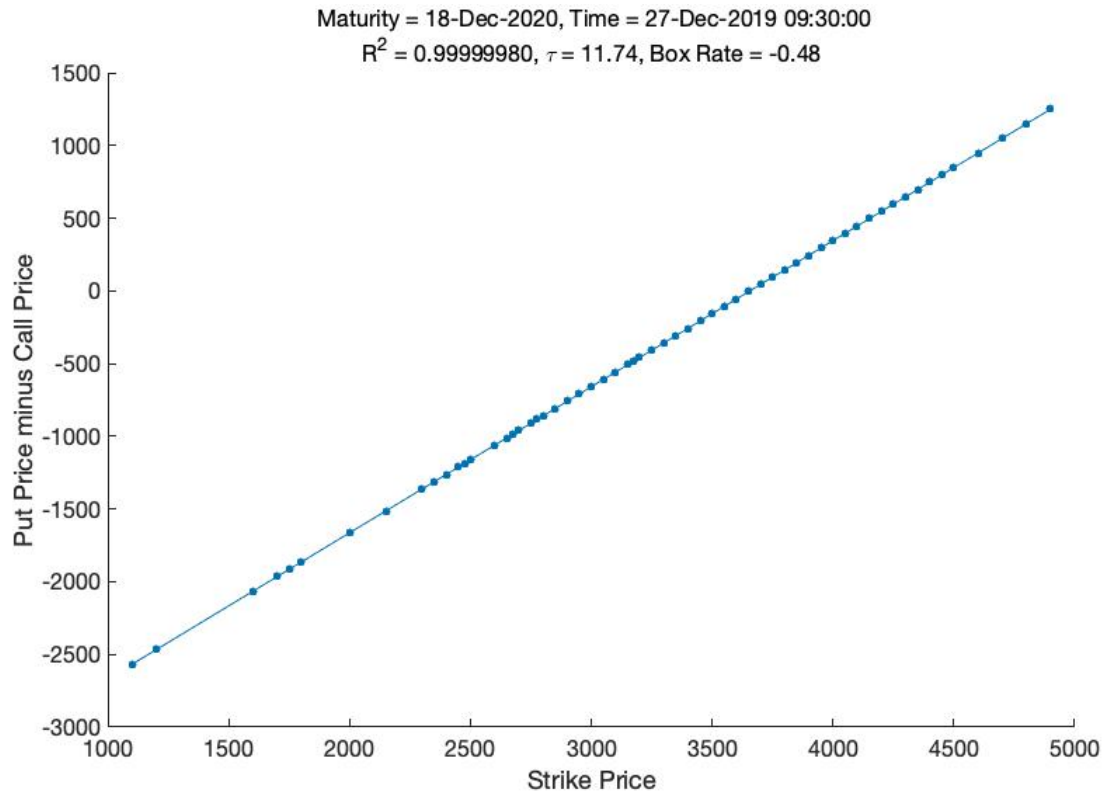


Figure 2. This figure provides illustrates the linear relationship between put minus call prices (using the mid-quote) and strike prices. The options in this example are Euro Stoxx 50 Index Options (OESX) traded on the EUREX exchange that are denominated in EUR. The data is from 9:30am on December 27, 2019 for options that mature in 357 calendar days on December 18, 2020. The estimate of the option-implied EUR risk-free rate is -0.48% .

Second, each country’s average convenience yield is closely related to its average nominal interest rate when rates are positive, with higher rate countries having higher convenience yields. However, convenience yields seem unrelated to interest rate levels when interest rates are negative.

Table 3 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 government 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. Notably, all countries have a positive average convenience yield, which means every country’s government debt has a lower interest rate than a risk-free rate inferred from options on the

country's major stock index. This provides robust evidence that in all countries, a demand for safe, money-like assets boosts the price of government debt strictly above the present value of the cash flows it pays implicit in a pricing kernel consistent with options prices.

The convenience yield for US debt is roughly average when compared to other countries, implying that the global role of the dollar does not give dollar-denominated safe assets an unusually large convenience yield. US bonds have an average convenience yield of roughly 34 basis points, with a nearly flat term structure of convenience yields across maturities. This is below the convenience yields of four currencies (Australia, Norway, Canada, Sweden) and above that of five (UK, Euro, Switzerland, Japan, Denmark). By our measure, the US seems to have average convenience yields that are near the middle of those in other countries. The highest convenience yields are in Australia (61-63 basis points across the available maturities), while Switzerland (2-18 basis points across maturities), Japan (11 basis points), and Denmark (15-17 basis points across maturities) have the lowest.

Table 1

Summary statistics: Average convenience yields, where .01 is a 1 percent yield. 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 | .0034 (.0003,5823) | .0035 (.0002,5961) | .0035 (.0002,5834) | .0035 (.0003,3667) | |
| UK | .0022 (.0008,1933) | .0030 (.0005,2609) | .0035 (.0003,3724) | .0038 (.0007,3724) | |
| Euro | .0029 (.0004,4751) | .0029 (.0003,4890) | .0027 (.0003,4982) | .0024 (.0002,4967) | .0021 (.0002,4856) |
| Switzerland | | | .0002 (.0002,5291) | .0014 (.0003,4578) | .0018 (.0003,4461) |
| Canada | .0047 (.0009,2633) | .0037 (.0004,2641) | .0036 (.0002,1857) | .0029 (.0002,1444) | |
| Australia | .0061 (.0011,1931) | .0063 (.0010,1964) | .0060 (.0006,684) | | |
| Denmark | .0017 (.0003 ,1227) | .0015 (.0006, 859) | | | |

As shown in Figure 3, the cross section of average convenience yields across countries is quite well explained by the average nominal interest rate in each country. Australia has the highest convenience yields as well as the highest nominal interest rates, while Denmark, Switzerland, and Japan have both low convenience yields and low interest rates. As shown in Table 3, a regression of each country's average one-year convenience yield (with a six-month

Table 2

Summary statistics: Average Bill Convenience Yields, where .01 is a 1 percent yield. Newey-West Standard Errors based on 100 day lag and number of observations in parentheses.

| Country | 3 Month | 6 Month | 1 Year |
|--------------------|--------------------|--------------------|--------------------|
| USA (Bill) | .0052 (.0003,6923) | .0049 (.0003,5966) | .0048 (.0004,4158) |
| UK (Bill) | .0023 (.0005,3464) | .0015 (.0003,769) | |
| Euro (Bill) | | .0035 (.0004,4783) | .0022 (.0003,3540) |
| Japan (Bill) | .0011 (.0009,1778) | | |
| Norway (Bill) | .0050 (.0004,2400) | .0050 (.0006,2015) | |
| Sweden (Bill) | .0037 (.0005,3002) | .0048 (.0006,3090) | |
| Switzerland (Bill) | .0025 (.0005,4869) | | |
| Canada (Bill) | .0050 (.0009,2703) | .0038 (.0005,2727) | .0036 (.0002,1921) |

maturity used for Sweden and Norway due to a lack of one-year maturity options) yields a slope parameter of .151, and a R-squared of .844. This implies that a one percentage point increase in interest rates is associated with a 15 basis point increase in convenience yields. Our cross-sectional evidence using data from many countries complements the analysis of 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, although convenience yields spike in financial crises without a rise in interest rates, requiring him to use the VIX as a control variable to measure periods of financial distress. In addition, our results suggest that convenience yield levels may be related to the carry trade, in which international investors borrow in low interest rate countries (like Japan) and lend in high interest rate countries (like Australia) in a manner that may impact the pricing of safe assets across countries.

A second tentative result from our summary statistics is that the relationship between the levels of interest rates and convenience yields breaks down when interest rates become negative. While we only have a few countries (Denmark, Japan, and Switzerland) that primarily experience negative interest rates in our sample, there does not seem to be an upward-sloping relationship between interest rates and convenience yields for these very low rate currencies. Our theoretical framework in section E presents one explanation for this result. When rates are positive, the liquidity benefits of cash and other safe assets such as

bank deposits are closely substitutable for each other. However, when rates are negative and cash dominates the return on other assets, the cost of holding large quantities of physical paper cash is not a cost shared by safe, money-like assets that can be traded electronically.

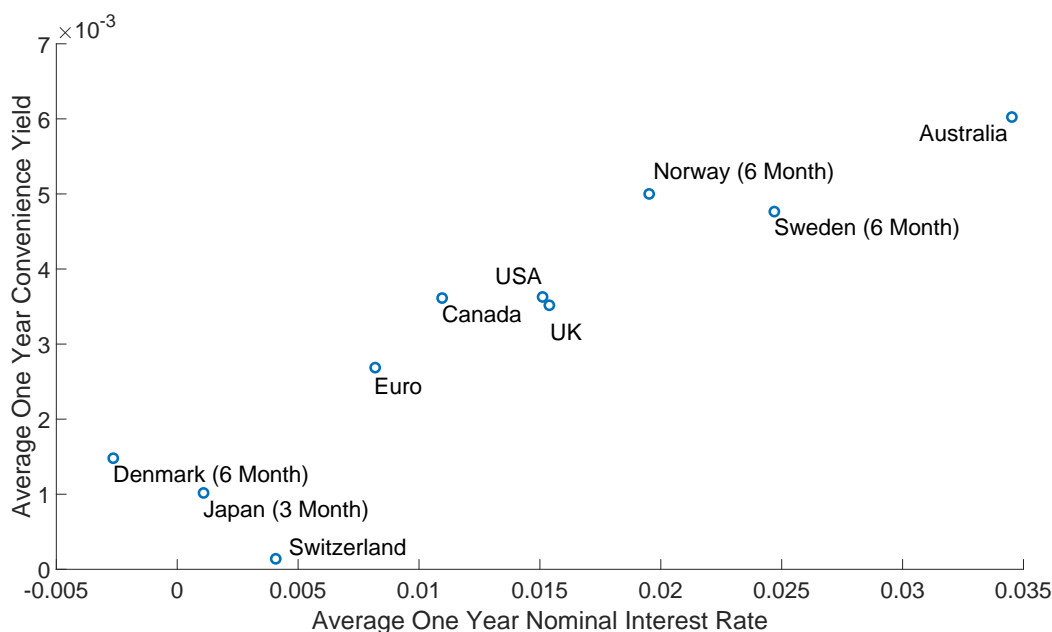


Figure 3. Average One-Year Convenience Yields and One-Year Government Yields Across Countries

Table 3. Cross Country Regressions of Average Interest Rate Spreads on Average Treasury Rates, 1-Year Maturity

| Coefficient | LIBOR-Treasury Spread | Box-Treasury Spread |
|-------------|-----------------------|---------------------|
| Intercept | 0.00341 (0.00072) | 0.00134 (0.0003744) |
| Slope | 0.04883 (0.04041) | 0.15084 (0.02294) |
| R-squared | 0.173 | 0.844 |

While our estimated convenience yield magnitudes are highly correlated with the level of nominal interest rates across countries, this relationship is weaker for the commonly used LIBOR rate. LIBOR is a survey-based measure 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 15.1 basis points larger Box-Treasury spread (so the Box rate is 115.1 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. Through the lense of our theoretical model below, the lower slope for LIBOR implies that it provides a convenience yield between that of Treasures and that of our box rate.

Precision of Estimated Rates

For our box rates to be precisely estimated, it is crucial that the put-call parity relationship that it exploits holds well in the data. One measure of the degree to which put-call parity holds is the R-squared of the regression in equation 2, since put-call parity holds exactly if and only if this regression has an R-squared of 1. Table 4 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, some of our later analysis using time series variation will be restricted to the four countries with the highest R-squared values.

Table 4

Summary Statistics : Average of daily median of R-squared of put-call parity regression in equation 2 used to estimate box rates.

| Country | Stock Index | Mean R-Squared | Days of Data | Start | End |
|-------------|--------------------|----------------|--------------|-----------|-----------|
| Australia | ASX 200 | 0.9999548 | 4578 | 1/2/2004 | 7/27/2020 |
| Norway | OBX 25 | 0.9999738 | 4464 | 1/3/2005 | 7/27/2020 |
| Denmark | OMX Copenhagen 25 | 0.9999788 | 2339 | 1/27/2012 | 6/30/2020 |
| Japan | Nikkei 225 | 0.9999853 | 4098 | 1/6/2005 | 7/27/2020 |
| Sweden | OMX Stockholm 30 | 0.9999871 | 4184 | 1/3/2005 | 6/30/2020 |
| Canada | TSX 60 | 0.9999901 | 3416 | 1/1/2010 | 3/6/2020 |
| UK | FTSE 100 | 0.9999907 | 4144 | 1/2/2004 | 7/27/2020 |
| Switzerland | Swiss Market Index | 0.9999919 | 4493 | 1/2/2004 | 7/27/2020 |
| Europe | STOXX | 0.9999962 | 4587 | 1/2/2004 | 7/27/2020 |
| US | S & P 500 | 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 box rates and for government bond yields. Covered interest parity (CIP) is a no-arbitrage relationship between risk-free rates in two difference countries, the spot exchange rate between the countries' currencies, and the forward exchange rate between their currencies. Suppose that one dollar can buy S_t units of foreign currency at time t , and promising one dollar in a forward contract in n periods can buy $F_{t,t+n}$ units of foreign currency in n periods. If $i_{t,t+n}^{\$}$ and $i_{t,t+n}^f$ are the n -period continuously compounded risk-free rates denominated in dollars and in foreign currency, then covered interest parity holds if

$$\exp(ni_{t,t+n}^{\$}) = \frac{F_{t,t+n}}{S_t} \exp(ni_{t,t+n}^f)$$

$$i_{t,t+n}^{\$} = \frac{1}{n} (\log(F_{t,t+n}) - \log(S_t)) + i_{t,t+n}^f.$$

The CIP relationship reflects the fact that home currency can be swapped into foreign currency today at exchange rate S_t , invested at the foreign rate $i_{t,t+n}^f$, and then swapped back to home currency at forward rate $F_{t,t+n}$ to construct a “synthetic dollar interest rate.”

In the absence of arbitrage, this synthetic rate must equal the dollar interest rate $i_{t,t+n}^{\$}$. We measure CIP deviations with the expression

$$CIPD_{t,t+n} = i_{t,t+n}^{\$} - \frac{1}{n}(\log(F_{t,t+n}) - \log(S_t)) + i_{t,t+n}^f.$$

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.

Our analysis of CIP deviations for both box rates and government bond yields allows us to determine the extent to which CIP deviations are due to a convenience yield for safe assets. Because our box rate CIP deviations are inferred only from the markets for equity derivatives and foreign exchange derivatives, they are an arbitrage spread between assets in two countries' financial markets that do not include the prices of any safe assets. Government bond CIP deviations, in contrast, are impacted by the convenience yield of government debt in both countries. We can decompose the CIP deviation for government debt between two countries as

$$CIPD_{t,t+n}^{gov} = i_{t,t+n}^{\$,gov} - \frac{1}{n}(\log(F_{t,t+n}) - \log(S_t)) + i_{t,t+n}^{f,gov}. \quad (5)$$

$$= \left(i_{t,t+n}^{\$,box} - \frac{1}{n}(\log(F_{t,t+n}) - \log(S_t)) + i_{t,t+n}^{f,box} \right) + [(i_{t,t+n}^{f,box} - i_{t,t+n}^{f,gov}) - (i_{t,t+n}^{\$,box} - i_{t,t+n}^{\$,gov})] \quad (6)$$

$$= CIPD_{t,t+n}^{box} + (CY_{t,t+n}^f - CY_{t,t+n}^{\$}). \quad (7)$$

The first term, $CIPD_{t,t+n}^{box}$ is inferred only from forward and spot currency exchange rates and from the prices of index options in each country. The second term, $(CY_{t,t+n}^f - CY_{t,t+n}^{\$})$ is the difference between the convenience yields we estimate in the foreign country and for the US using our box rates and government bond yields. 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 ($CY_{i,t+n}^f - CY_{i,t+n}^{\$}$) 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.

We have two main results on the cross-section of CIP deviations. First, every country has a negative box CIP deviation with respect to the dollar, with fairly little heterogeneity in the size of the CIP deviation across non-US countries. This implies that the dollar box rate is strictly below any synthetic dollar rate constructed with a foreign box rate and foreign exchange derivatives. While previous work such as (Du et al., 2018b,a) show that most countries have negative CIP deviations with respect to the dollar using risk-free rates other than our box rate, countries such as Australia and New Zealand tend to be exceptions to this rule. In contrast, our results are consistent with there being a transactions/regulatory cost of a US dealer bank or hedge fund doing international arbitrage that does not vary across countries. Moreover, as we discuss in our theoretical model, our results are consistent with the US financial sector playing a unique role in the global financial system, with the marginal arbitrageur paying a cost to borrow risk-free in the US and lend risk-free in foreign countries.

Second, unlike for government CIP deviations, the magnitude of a country's box CIP deviation is close to uncorrelated with the level of interest rates in the country. Unlike for box rates, Du et al. (2018b) and Du et al. (2018a) show that the size of CIP deviations using LIBOR or government debt yields in different countries are predicted quite accurately by the country's level of interest rates. Our result for box CIP deviations, combined with our previous result that the level of interest rates is a good predictor of the size of the convenience yield on a country's government debt, imply that the cross-section of government debt CIP deviations is best explained by the size of safe asset convenience yields across countries.

Tables 5 and 6 present summary statistics on average CIP deviations for box rates and

Table 5

Summary statistics: average box rate covered interest parity deviations relative to the dollar. A deviation of .01 represents a 1 percent yield spread, where the sign convention is that a negative spread reflects that dollar box rates are lower than a rate constructed with foreign box rates and foreign exchange transactions.

| Country | 3 Month | 6 Month | 1 Year | 2 Year |
|-------------|-----------------|-----------------|-----------------|-----------------|
| Australia | -0.0008 (.0011) | -0.0010 (.0010) | -0.0009 (.0008) | |
| Canada | -0.0019 (.0010) | -0.0012 (.0006) | -0.0011 (.0002) | |
| Switzerland | -0.0008 (.0003) | -0.0011 (.0003) | -0.0014 (.0004) | -0.0020 (.0004) |
| Euro | -0.0004 (.0003) | -0.0005 (.0003) | -0.0008 (.0003) | -0.0012 (.0003) |
| UK | 0.0010 (.0005) | -0.0001 (.0003) | -0.0004 (.0003) | -.0006 (.0008) |
| Japan | -0.0014 (.0014) | | | |
| Norway | -0.0012 (.0005) | -0.0011 (.0006) | | |
| Sweden | -0.0013 (.0005) | -0.0023 (.0006) | | |
| Denmark | -.0008 (.0004) | -.0013 (.0004) | | |

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, Denmark, and Japan, government CIP deviations are negative and the largest in magnitude, in the range of -30 to -50 basis points. As we show visually in Figure 4, 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.

Unlike previous work examining other interest rates, we find no relationship between a country's interest rate level and the size of its box CIP deviation. For example, Australia and Japan have average box CIP deviations that are quite close to each other (for example, a one-year CIP deviation of -10 basis points for Australia and -11 basis points for Japan). Figure 5 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. In Table 7,

we show that a country's average one-year interest rate has effectively no predictive power for the size of its average box CIP deviation, with an R-squared of only .0000398. This is quite unlike CIP deviations constructed with government rates. Table 7 also shows that a country's average interest rate level predicts the government CIP deviation magnitude with an R-squared of .656, and a 1 percent interest rate increase is associated with an 11 basis point increase in its CIP deviation.

Table 6

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

| Country | 3 Month | 6 Month | 1 Year | 2 Year |
|-------------|-----------------|-----------------|-----------------|------------------|
| Australia | 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) | | |
| Denmark | -.0020 (.0003) | -.0028 (.0004) | -.0044 (.0003) | |

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 7, the convenience yield difference term $CY_f - CY_s$ is the main force that drives the variation of $CIPD_{gov}$ across countries. The overall level of government CIP deviations, however, which averages -16 basis points for the data points in Figure 4 is driven primarily by the average box CIP deviation of -11 basis points for the data points in Figure 5. 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 $CY_f - CY_s$ in equation 7. Our results are related to evidence presented by

Du et al. (2018b) that CIP deviations are related to bank regulation. 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 arbitrated 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.

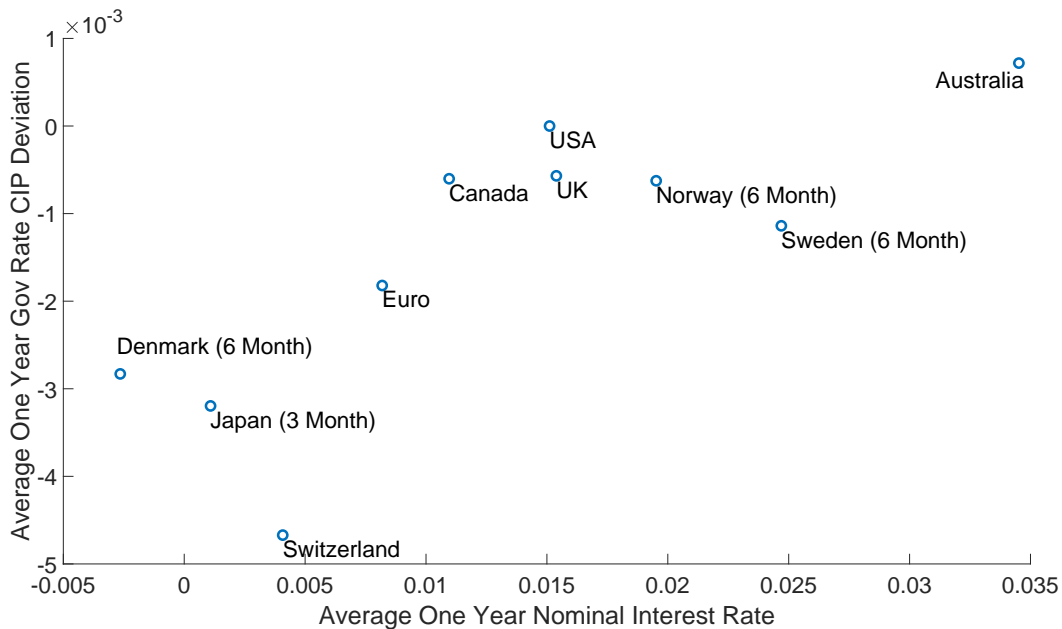


Figure 4. Cross-Section of Nominal Interest Rates and Government CIP Deviations

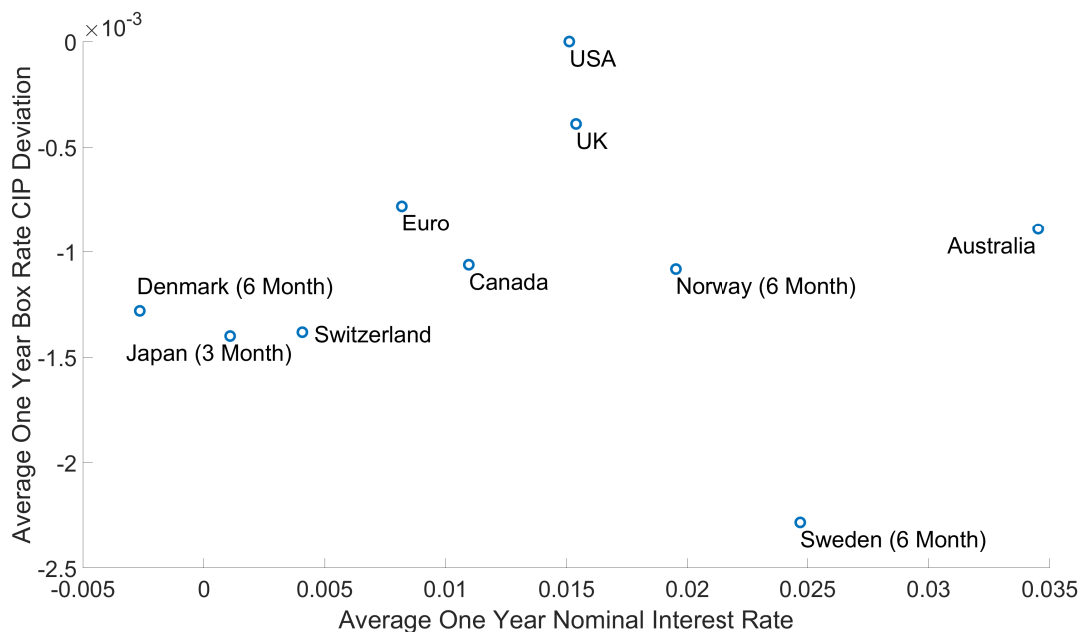


Figure 5. Cross-Section of Nominal Interest Rates and Box CIP Deviations

Table 7. 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 | -0.003088 (0.000527) | -0.001169 (0.000284) |
| Slope | 0.112774 (0.030847) | -0.000277 (0.0166190) |
| R-squared | 0.656 | 0.0000398 |

E Theoretical Explanation

This section presents a simple theoretical model related to Nagel (2016) that rationalizes our cross-sectional findings.

Consumer In each country j , asset k pays a real cash flow δ_{jk} , denominated in units of the local consumption good. In addition, there are two “special assets” demanded by consumers—deposits and cash. Deposits and cash both provide liquidity services to consumers that we model with money in the utility function. Deposits pay a risk-free nominal interest rate $i_{j,d,t}$ while cash pays a nominal interest rate of 0. The consumer in county j is endowed with

wealth W_j and maximizes their utility

$$u(c_{jt}) + \beta E_t u(c_{j,t+1}) + v(C_{jt}, D_{jt}) \quad (8)$$

where capital C is real cash holdings and D is real deposit holdings (that is, nominal holdings divided by the current price level P_{jt}). We impose the functional form

$$v(C_{jt}, D_{jt}) = F(\min(C_{jt}, C^*) + \kappa D_{jt}) - G(\max(C_{jt} - C^*, 0)) \quad (9)$$

on the consumer's benefits of holding liquid assets, where F and G are strictly increasing functions and $0 > \kappa > 1$ is a constant. Up to a satiation point C^* , cash provides liquidity benefits that are perfectly substitutable for the liquidity benefits κD_{jt} . Because $\kappa < 1$, cash is strictly more liquid than deposits, so deposits can earn a positive interest rate when cash pays no interest. Beyond the satiation point C^* , cash no longer provides liquidity benefits, and the cost function G reflects fact that it is a physical piece of paper that is costly to store. This cost stops consumers from substituting entirely to cash when interest rates are negative. G is additively separable from F to reflect the fact that the physical storage costs of cash are not shared by bank deposits or electronic assets. We show in appendix A that the deposit spread is

$$i_{jt} - i_{d,jt} = i_{jt} \frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial D_{jt}}}{\frac{\partial v(C_{jt}, D_{jt})}{\partial C_{jt}}}, \quad (10)$$

where i_{jt} is the nominal risk-free rate the consumer would accept for an asset that provides no special liquidity benefits.

When the nominal interest rate is positive, cash must provides a positive liquidity benefit so $C_{jt} < C^*$. In this case, $\frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial D_{jt}}}{\frac{\partial v(C_{jt}, D_{jt})}{\partial C_{jt}}} = \kappa$ and we get a positive linear relationship between

nominal interest rates and the convenience yields of deposits

$$i_{jt} - i_{d,jt} = i_{jt}\kappa. \quad (11)$$

When the nominal interest rate is negative, we must have that $C_{jt} > C^*$. In this setting, we have that

$$\frac{\partial v(C_{jt}, D_{jt})}{\partial C_{jt}} = -G'(C_{jt} - C^*), \quad \frac{\partial v(C_{jt}, D_{jt})}{\partial D_{jt}} = F'(C^* + \kappa D_{jt})\kappa. \quad (12)$$

In this case, the liquidity benefit of buying additional deposits is not impacted by the supply of cash. When nominal interest rates are negative, changes in the supply of cash impact the nominal rate without changing deposit convenience yields, if macro variables such as aggregate consumption are held fixed. Changes in deposit supply impact deposit convenience yields without having any impact on the nominal interest rate, again assuming total consumption and the money supply are held fixed.

Supply of deposits from intermediary. The deposits held by consumers are produced by financial intermediaries. An intermediary in country j holds a portfolio with weight vector w_{jk}^I on asset k . The intermediary raises equity E_{jt} and deposits D_{jt} and maximizes the difference

$$E_{jt} + D_{jt} - \sum w_{jk}^I p_{jk} \quad (13)$$

between the amount of funding it can raise and the cost of the portfolio it must buy to back the deposits and equity it issues. The intermediary's equity and deposits are sold to the consumer and are therefore priced by its first-order conditions (appendix equations A3 and A4). The intermediary must satisfy a regulatory constraint $f(w_j^I) - D_{jt} \geq 0$, which ensures the solvency of its deposits. One specific regulatory constraint we consider is that in every

state of the world, the intermediary's portfolio must satisfy

$$\sum (1 - (\lambda + \lambda_k^*)) w_{jk}^I \delta_{jk} \geq D_{jt}. \quad (14)$$

This constraint can be interpreted as a risk or liquidity weighted capital requirement. For most assets, we think of λ_k^* being equal to 0, but some special/convenient safe assets such as Treasuries receive preferential regulatory treatment where $\lambda_k^* < 0$. As a result, holding a Treasury allows the intermediary to issue strictly more deposits than it could by holding other assets with $\lambda_k^* = 0$ that provide the same risk-free payoff.

If this is a risk-free asset that pays an interest rate $1 + i_{jk,t}$ and costs 1, then appendix B shows that

$$i_{jt} - i_{jk,t} = \frac{\partial f}{\partial w_{jk}} (i_{jt} - i_{d,jt}). \quad (15)$$

This implies that the convenience yield on any intermediated safe asset is the product of how many deposits it backs times the convenience yield of a deposit. For the particular capital requirement we consider in equation 14, this becomes

$$i_{jt} - i_{jk,t} = (1 - (\lambda + \lambda_k^*)) (i_{jt} - i_{d,jt}). \quad (16)$$

The convenience yield on an asset is determined both by how much it relaxes the intermediary's constraint and by the convenience of deposits. For this specific regulatory constraint, deposit convenience yields are a sufficient statistic for all convenience yields, including assets held by the intermediary. When rates are positive, this implies that the nominal interest rate determines the convenience yield of assets owned by the intermediary too. This is because an asset's convenience yield reflects both the quantity of deposits it is able to back (which is a constant for any risk-free asset) and the benefit to the intermediary of issuing deposits, which is determined by the nominal interest rate.

International Financial Arbitrage In addition to the intermediary that invests in domestic markets to back deposits, there is an international “hedge fund/dealer bank” that can trade across countries. It is not funded directly by deposits but by a mix of equity financing from consumers and risk-free wholesale funding from the domestic intermediary. This is consistent with the result in Anderson et al. (2021) that international arbitrage trades are financed primarily with wholesale funding rather than retail bank deposits. The debt of the international dealer is a non-special asset for which $\lambda_k = 0$, and special assets it buys in other currencies do not provide it any special liquidity/convenience. Let δ_{t+1}^{Int} be the payoff of the intermediary’s portfolio (in units of local consumption), and $\delta_{t+1}^{Int,min}$ be the lowest possible realization of this payoff. The dealer faces the regulatory constraint that it can only promise a payoff up to $(1 - \lambda)\delta_{t+1}^{Int,min}$ of risk-free borrowing. The value of the international dealer at time t is therefore

$$(1 - \lambda)\delta_{t+1}^{Int,min} \frac{1}{1 + i_{rf}} + \beta E_t \frac{u'(c_{t+1})}{u'(c_t)} [\delta_{int} - \delta_{min,int}(1 - \lambda)] \quad (17)$$

where i_{rf} is the risk-free rate at which the dealer can borrow, solving equation 16 with $\lambda_k^*=0$. The willingness to pay for a synthetic risk-free asset composed of foreign assets that pays 1 is therefore

$$(1 - \lambda) \frac{1}{1 + i_{rf}} + \lambda \beta E_t \frac{u'(c_{t+1})}{u'(c_t)} \quad (18)$$

which is strictly above the risk-free rate i_{rf} at which the intermediary can borrow. However, all synthetic foreign assets have the same spread above this risk-free rate, as is true on average on our cross section of box rates. If we suppose that the international dealer bank sector is primary financed in dollars, then dollar yields are below synthetic dollar yields from non-dollar countries. However, all non-dollar countries have the same synthetic dollar yield. Under the assumption that the international financial system is disproportionately financed in dollars and uses this funding to invest in other currencies, we can interpret i_{rf} as the dollar box rate, since this is a non-special risk-free rate at which arbitrageurs can borrow.

The strictly higher interest rate $i_{rf,synth}$ implied by equation 18 satisfies

$$[(1 - \lambda) \frac{1}{1 + i_{rf}} + \lambda \beta E_t \frac{u'(c_{t+1})}{u'(c_t)}](1 + i_{rf,synth}) = 1. \quad (19)$$

Mapping this to data, we interpret $i_{rf,synth} - i_{rf}$ as a box CIP deviation, since this is an arbitrage spread between two “non-special” interest rates that is not associated with an asset with special regulatory treatment. In contrast, the CIP deviation derived using “special” risk-free rates is equal to the box CIP deviation plus a difference in convenience yields as determined by equation 16. For countries with positive interest rates, these convenience yields are increasing in the level of interest rates, explaining why government debt CIP deviations vary with the level of interest rates across countries.

F 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 6 for the four currencies with the 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. Appendix figures A1 and A2 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 7 and 8.

Although the US does not have an unusually large convenience yield, the US-centered 2008 financial crisis had unusually large spillovers on convenience yields in other countries. In Figure 6, 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 only increase modestly. 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.

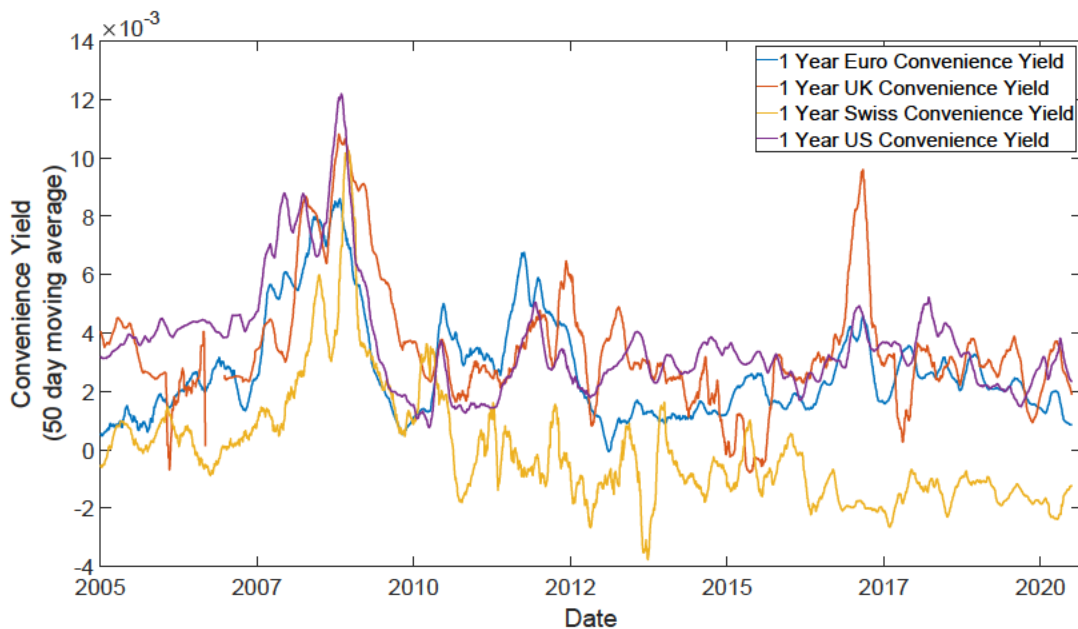


Figure 6. One-Year Convenience Yields, Measured as One-Year Box Rates Minus One-Year Government Yields, for the US, UK, Euro, and Switzerland.

For the four currencies in Figure 6, we find that convenience yields tend to spike during financial crises, and that a country's own convenience yields spike particularly during a domestic financial crisis. While the 2008 crisis, which originated in the US, was a period where dollar safe assets had a particularly large convenience yield, we do not find that this is the case in crises that originate in other countries. The Euro crisis which peaked in 2010-2012 has Euro convenience yields larger than those in other countries, while during the Brexit panic of 2016 we find UK convenience yields growing far more than in other countries. The difference between a US and foreign convenience yield, which contributes to the size of CIP

deviations as shown in equation 7, is not generally larger in financial crises than in other times.

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 US crisis, 2010-2012 Euro crisis, and somewhat during the 2016 Brexit crisis. Smaller convenience yield movements outside of documented 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.

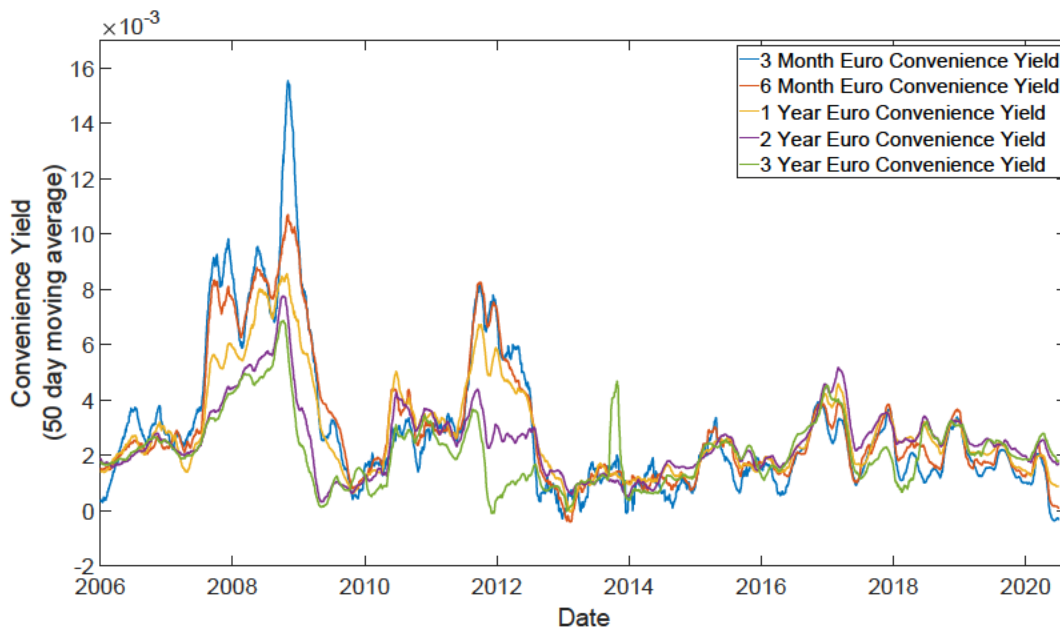


Figure 7. Term Structure of Euro Convenience Yields Over Time

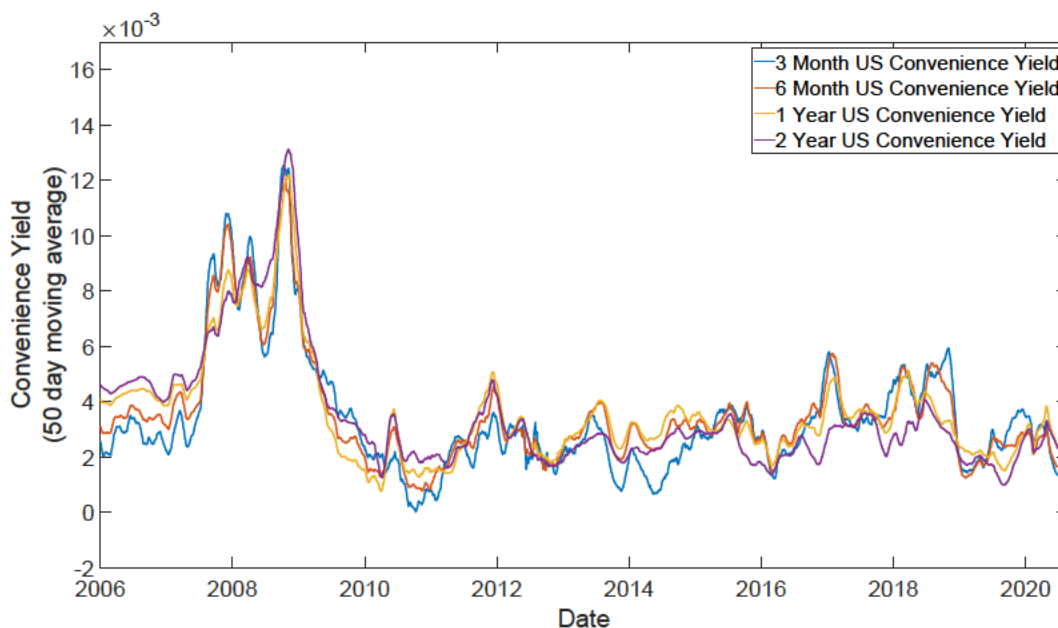


Figure 8. Term Structure of US Convenience Yields Over Time

G 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 7, this section aims to understand whether a special demand for dollar-denominated safe assets is 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, always

moving in the same direction regardless of the source of the crisis. In the 2008-2009 US financial crisis, the 2011-2012 European financial crisis, and the financial turmoil surrounding Brexit in 2016, 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 6), 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 9. This is unlike the behaviour of the convenience yields themselves, which grow largest in the US during the US crisis, largest in Europe during the Euro crisis, and largest in the UK during the Brexit crisis. The increase in box CIP deviations, with dollar yields falling relative to synthetic dollar yields manufactured with foreign assets, in all financial crises is one dimension in which the US seems to play a unique role in the global financial system.

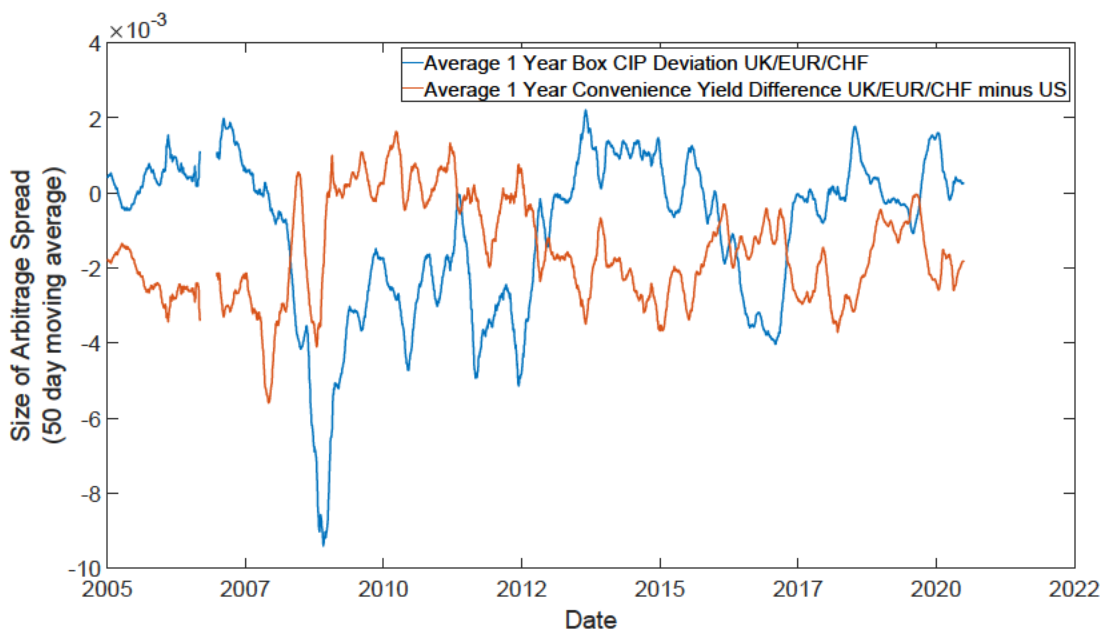


Figure 9. Box CIP deviations and Convenience Yield Differences Over Time

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 to roughly 40 basis points, this level that was fairly average in the pre-2008 part of the sample. During the

Table 8

| | 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.

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 time series correlation between these two series is -.56. Because the sum of these two series (as implied by equation 7) 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 8 provides additional 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 with an R-squared of just .0266.

H Convenience Yields and CIP Deviations in the 2020 Covid-19 Crisis

This section analyzes the behavior of CIP deviations and convenience yields during the brief period of financial turmoil in March 2020 that occurred 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 10 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 11 that box CIP deviations behaved similarly in this crisis as in previous ones. Across all maturities from six months to two years¹ 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 constructed from FX forwards and foreign option prices. As shown in Figure 12, 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 9. 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 12 in March 2020.

I Convenience Yields, CIP Deviations, and Exchange Rates

This section analyzes the relationship between exchange rates, convenience yields, and our box rate CIP deviation measures. We first analyze the ability of our convenience yield and box CIP measures to forecast bilateral exchange rates. This follows Engel and Wu

¹We find similar results at a 3 month maturity, though the magnitudes are so big as to be difficult to plot in a single figure.

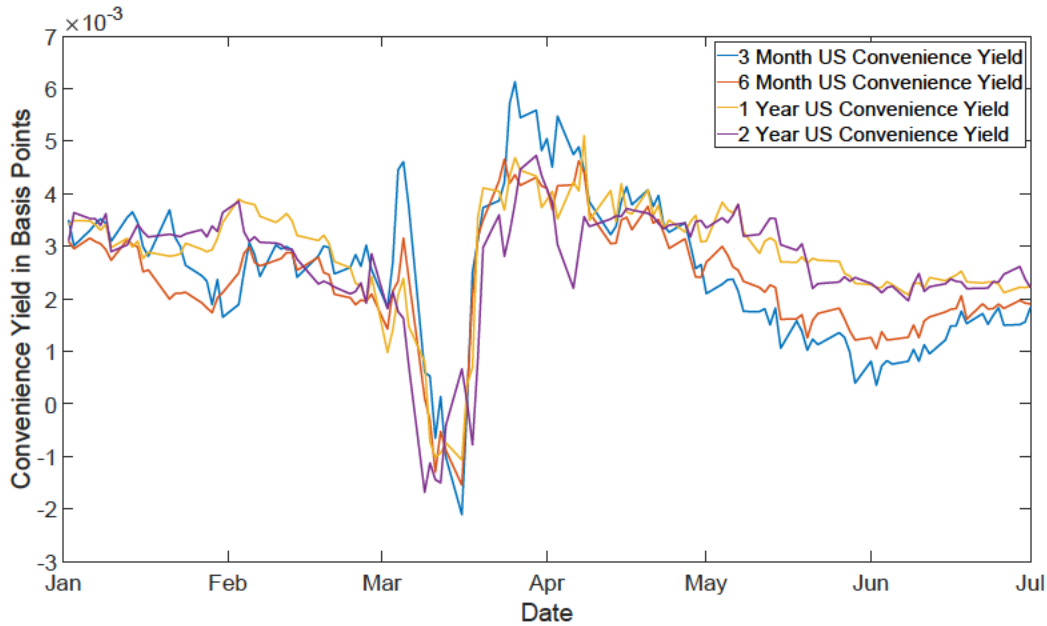


Figure 10. US Convenience Yields during 2020 Covid-19 Crisis

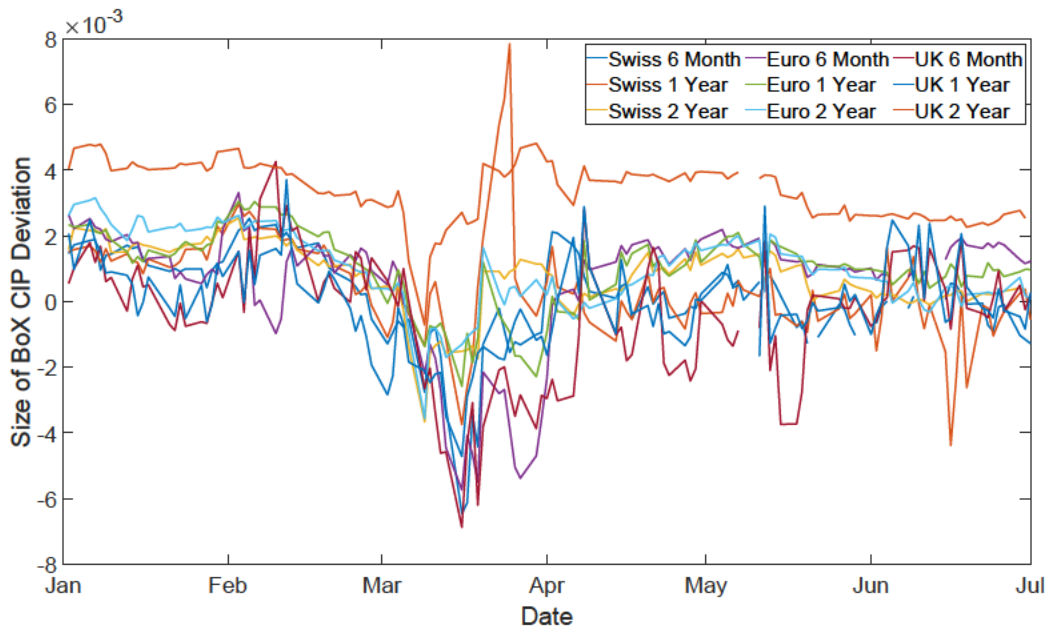


Figure 11. Box CIP Deviations During 2020 Covid-19 Crisis

(2022), who show that CIP deviations on government debt are an extremely useful variable for forecasting bilateral exchange rates. By decomposing the government CIP deviation into the sum of a box CIP deviation and the difference between a country’s convenience yield and that of the dollar, we demonstrate that both terms are useful for exchange rate forecasting.

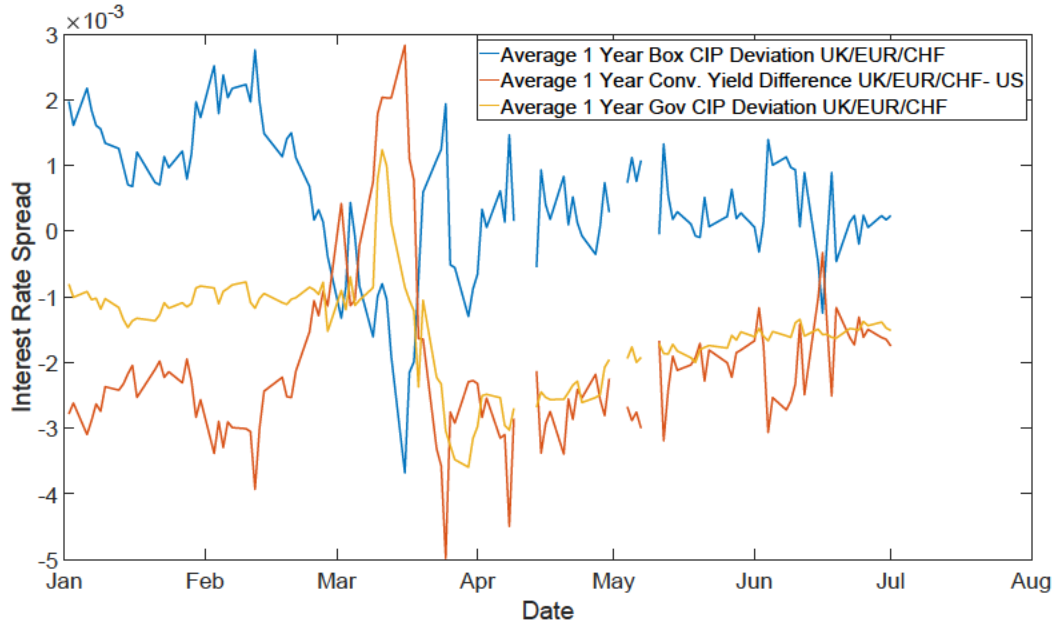


Figure 12. Average Box CIP, Convenience Yield Differences, and Government CIP Deviations During 2020 Covid-19 Crisis

Similar to Engel and Wu (2022), our benchmark specification is a monthly regression

$$\Delta s_{j,t+1} = \alpha_j + \beta_1 \Delta \text{BoxCIP}_{j,t} + \beta_2 \text{BoxCIP}_{j,t-1} + \beta_3 \Delta \text{CYdiff}_{j,t} + \beta_4 \text{CYdiff}_{j,t-1} + u_{j,t+1}, \quad (20)$$

where $s_{j,t+1}$ is the change in the log exchange rate of currency j with respect to the dollar from month t to month $t + 1$, with the convention that it is positive when the dollar appreciates. $\text{BoxCIP}_{j,t-1}$ is the level of the country's box CIP with respect to the dollar, measured as a yield spread, with the convention that it is positive when a country's synthetic dollar yield is below the true dollar box rate. $\text{CYdiff}_{j,t-1}$ is the difference between a country's convenience yield (difference between box rate and government rate) and that of the dollar, with the convention that it is positive when a country's convenience yield is larger than that of the dollar. A Δ represents a change in a variable relative to the previous month. We use the exchange rates of the British Pound, Euro, and Swiss Franc against the dollar in our benchmark analysis.

We present our baseline results in the first column of Table 9, as well as a second predictive

regression for the contemporaneous exchange rate change $\Delta s_{j,t}$ in the second column. In both specifications, a 100 basis point reduction in a synthetic dollar yield constructed with a country's box rate relative to the actual dollar box rate is associated with a 5 percent appreciation in its exchange rate. This occurs both contemporaneously as well as in terms of a prediction for next month's exchange rate change. This implies that in periods of crises where most countries have high synthetic dollar yields, with all 3 currencies we consider having box CIP deviation spreads of 100 basis points or more in the worst of the 2008 crisis, their currency should meaningfully depreciate against the dollar. Similarly, when a country's convenience yield grows 100 basis points larger than that of the dollar, both specifications imply that its exchange rate should appreciate roughly 4 percent relative to that of the dollar. Appendix Table A2 shows that our results are similar across all three currencies we use when analyzed separately.

This is somewhat larger than the peak in each country's convenience yield difference relative to the dollar (35 basis points for the Euro, 20 basis points for Switzerland, 60 basis points for the UK), although existing fluctuations still forecast exchange rate movements in the magnitude of up to around 2 percentage points. That said, box CIP deviations spike during crises and revert during tranquil times with greater fluctuations than changes in convenience yield differences. This greater variability implies that box CIP deviations can account for a larger share of the variance in exchange rates than convenience yield differences can. This suggests that the ability of government CIP deviations to forecast exchange rates has more to do with arbitrage frictions between international financial markets rather than movements in the convenience yields of safe assets in particular.

Our second analysis of the relationship between CIP deviations and exchange rates examines the ability of exchange rate movements to forecast changes in CIP deviations. This follows Avdjiev et al. (2019), who show that fluctuations of the dollar against a broad basket of other currencies comove strongly with changes in CIP deviations constructed from interest rates on government debt. Conditional on the return on the so-called "broad dollar", a

Table 9

| Variable | Coefficient | Standard Error | Coefficient | Standard Error |
|-----------------------|--------------------|----------------|------------------|----------------|
| $\Delta BoxCIP_{j,t}$ | - 5.027697 | 2.492346 | -4.757815 | 1.984936 |
| $BoxCIP_{j,t-1}$ | -.850735 | .8469892 | -1.836529 | .9816004 |
| $\Delta CYdiff_{j,t}$ | -3.994989 | 1.859614 | -4.190793 | 2.087555 |
| $CYdiff_{j,t-1}$ | -.9276748 | .9514835 | -1.954635 | .9676637 |
| R-squared: | 0.0531 | | 0.0626 | |
| Predicted variable | $\Delta s_{j,t+1}$ | | $\Delta s_{j,t}$ | |

Monthly Exchange Rate Forecast Regressions, following Engel and Wu (2022). Monthly regression from Jan 2004 to July 2020.

country's bilateral exchange rate with the dollar has almost no additional predictive power for the size of its CIP deviation. We show that a similar result holds for box rate CIP deviations, but that the difference between a country's convenience yield and that of the US is nearly uncorrelated with fluctuations in the broad dollar exchange rate. Under the interpretation of Avdjiev et al. (2019) that fluctuations in the broad dollar are a good barometer for the severity of global financial frictions, this provides additional evidence that box CIP deviations seem to spike during financial crises but that convenience yield differences do not.

We run the regression

$$\Delta x_{jt} = \alpha_j + \beta \Delta Dollar_t + \gamma \Delta BER_{jt} + \epsilon_{jt} \quad (21)$$

where $\Delta Dollar_t$ denotes a change in the Federal Reserve Board (FRB) US trade-weighted broad dollar index and ΔBER_{jt} denotes the change in a country's bilateral exchange rate with the dollar. We use this to predict both x_{jt} as a country's box CIP deviation with respect to the dollar and then again as x_{jt} representing the difference between a country's convenience yield and that for dollar safe assets. We report our results in Table 10 and find meaningful predictive power only for box CIP deviations and not for convenience yield differences. However, a country's bilateral exchange rate provides effectively no additional predictive power for box CIP deviations once the change in the broad dollar index is included.

Our results imply that a one percentage point increase in the broad dollar is associated with a 1.72 basis point increase in the one-year box CIP deviation, very close to the benchmark result of 2.1 basis points reported by Avdjiev et al. (2019). Relative to this existing work, our contribution is to show that this result is due in our sample entirely to fluctuations in box CIP deviations and not to differences in a country’s convenience yield relative to the dollar. This is consistent with our results above that box CIP deviations spike during financial crises (during which the dollar also tends to appreciate) and confirms that dollar convenience yields are not unusually large during crises relative to those of other countries.

Table 10

| | | |
|-------------------|-------------------|--------------------|
| ΔBER_{jt} | .14067 (.34512) | - .54987 (.23005) |
| $\Delta Dollar_t$ | -1.72364 (.55433) | |
| R-squared | 0.0304 | 0.0098 |

Prediction of Box CIP deviation (in basis points) using bilateral exchange rate and broad dollar exchange rate. Monthly regression from Jan 2004 to July 2020 using data from the UK, Europe, and Switerland relative to the US.

| | | |
|-------------------|-------------------|------------------|
| ΔBER_{jt} | .26065 (.5336) | .13694 (.22187) |
| $\Delta Dollar_t$ | .05727 (.33221) | |
| R-squared | 0.0017 | .0008 |

Prediction of convenience yield differences (in basis points) using bilateral exchange rate and broad dollar exchange rate. Monthly regression from Jan 2004 to July 2020 using data from the UK, Europe, and Switerland relative to the US.

J Convenience Yields and Interest Rates: Panel Evidence

This section combines the cross-sectional and time-series evidence to provide a panel perspective on the relationship between the size of a country’s convenience yield and the level of its nominal interest rate. The results are related to Nagel (2016), who shows in US time-series data that the spread between repo rates and Treasury bill yields (his convenience yield measure) can be explained well using the level of interest rates together with the VIX on the S&P 500 as a proxy for periods of financial uncertainty. Column (1) of table 11 regresses

the convenience yield for the US onto the federal funds rate and the VIX. An increase of 1 percentage point in the federal funds rate is associated with an increase in the convenience yield estimate of 5.3 basis points, and an increase in the VIX by 10 percentage points is associated with a 9.5 bps increase in the convenience yield. The analogous estimates from Nagel (2016) are 6.5 bps and 9.6bps, quite similar to our results. Columns (2) and (3) report the analogous results for EUR and CHF, showing that for the three countries with the most precisely estimated box rates convenience yield fluctuations are predicted well by the VIX together with the level of nominal interest rates.

Columns (4-6) expand the analysis by running panel regressions that include option-implied convenience yields for all of the ten countries that we consider in our analysis. The dependent variable is the monthly average of the option-implied convenience yield for each country. We use a one-year maturity for all countries except for SEK, NOK, DKK where we use the six-month maturity and for JPY where we use the three-month maturity due to the availability of more observations of precisely estimated box rates at these shorter maturities for these countries. We find an even stronger relationship between interest rates and nominal interest rates here. With time fixed effects, that control even better than the VIX does for periods of financial distress, we end up with a 17 basis point increase in convenience yields resulting from a 1 percent increase in interest rates. This is quite close to the 15 basis point cross-sectional result in Table 3.

Finally, in Table 12, we strengthen the tentative evidence from Figure 3 that interest rates lose their ability to predict convenience yields when they are negative. We split our sample into a subset where the nominal interest rate is positive and where it is negative, and run the same regression separately on these two samples. The within R-squared of predicting convenience yields with nominal interest rates falls to .003 on this subsample, with each country's convenience yield predicted well by a fixed effect for that country. This is consistent with our theoretical result in equation 12 that nominal interest rates are no longer a sufficient statistic for the level of convenience yields once interest rates pass below

Table: Convenience Yield Panel Regressions

The sample period is 2002 to July 2020 as before and includes all calendar months for each currency in which data is available

| | (1) | (2) | (3) | (4) | (5) | (6) |
|--------------------------|---------|---------|---------|----------|----------|---------|
| Central Bank Policy Rate | 5.34*** | 3.67 | 9.45*** | 10.25*** | 17.11*** | 6.36*** |
| | (1.42) | (3.48) | (1.99) | (1.55) | (2.15) | (1.13) |
| VIX | 0.95** | 0.76*** | 0.99** | 0.85*** | | 0.95*** |
| | (0.47) | (0.25) | (0.38) | (0.28) | | (0.23) |
| R-squared adjusted | .326 | .229 | .483 | .22 | .324 | .449 |
| Within R-squared | | | | .222 | .254 | .177 |
| Currency | USD | EUR | CHF | ALL | ALL | ALL |
| Fixed Effects | None | None | None | None | TE | CE |
| Observations | 222 | 223 | 217 | 1324 | 1324 | 1324 |

Notes: HAC standard errors (12 lags) in parentheses, * $p < .10$, ** $p < .05$, *** $p < .01$

0.

K 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 13, we plot a weighted average of the R-squareds of all currencies except that of Australia², with the weights determined by constructing the first principal component of the R-square time series and then normalized 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 the magnitudes of various financial crises with this trend removed, Figure 14 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

²Because Australia's rates are the most volatile, a principal component would put large weight on this single currency.

Table: Convenience Yield Panel Regressions: Positive and Negative Interest Rates

This table2...

| | (1) | (2) |
|--------------------------|----------------------------|--------------------------|
| Central Bank Policy Rate | 5.660629 *** (.7042305) | .818167 (6.39301) |
| VIX | 1.217442 *** (.0943668) | .1167204** (.1204906) |
| R-squared adjusted | 0.4777 | 0.4438 |
| Within R-squared | 0.1929 | 0.0030 |
| Currency | ALL | ALL |
| Fixed Effects | CE | CE |
| Observations | 1251 | 329 |
| Interest rate levels | only positive | only negative |

Notes: HAC standard errors (12 lags) in parentheses, * $p < .10$, ** $p < .05$, *** $p < .01$

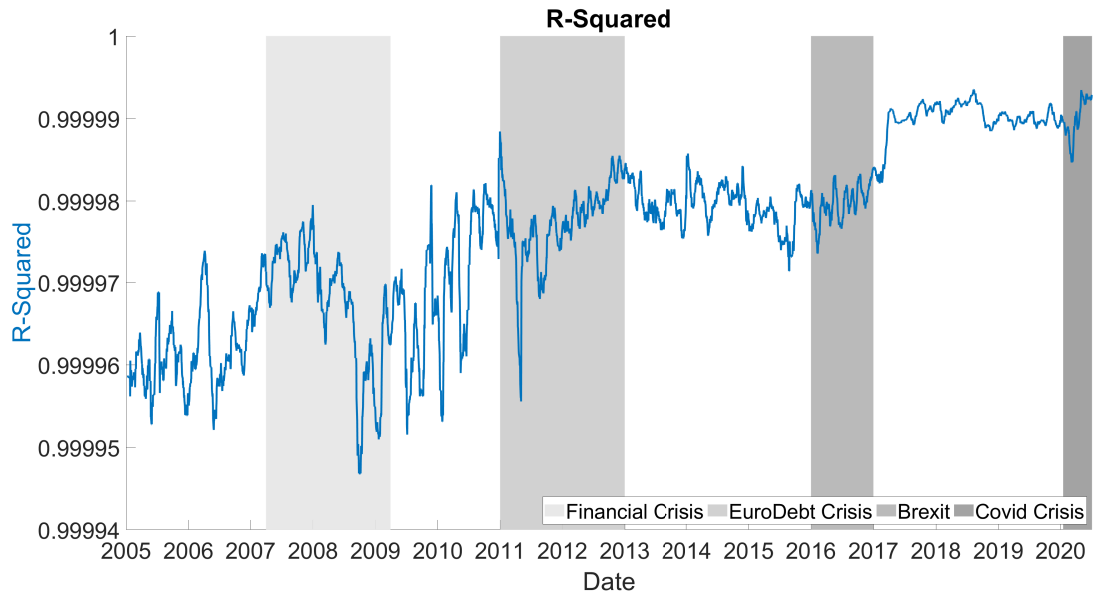


Figure 13. Time series of the first principal component of normalized R-squareds of put-call parity regressions. For each currency and each day, we take the average R-squared of our put-call parity regression across different maturities of the subset of R-squareds above .9999. The chart plots a weighted 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).

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-19 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

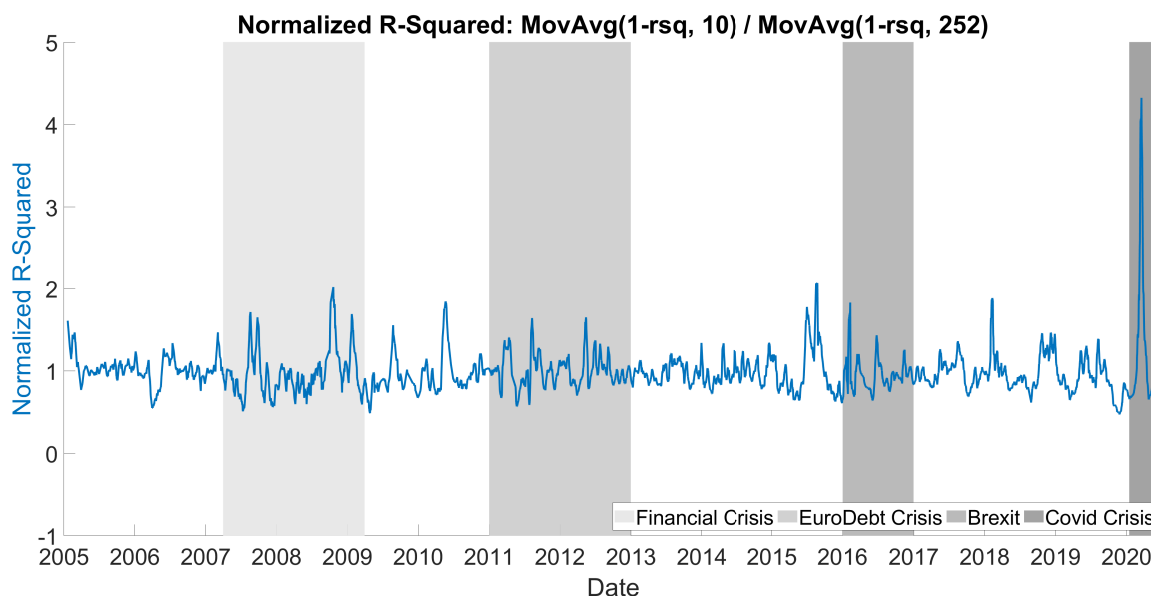


Figure 14. Time series of the first principal component of normalized R-squareds of put-call parity regressions. For each currency and each day, we take the average R-squared of our put-call parity regression across different maturities of the subset of R-squareds above .9999. We then compute the ratio 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-19 crisis did not, it makes sense that convenience yields are large particularly in 2008 and 2011-2012. The Covid-19 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.

L Conclusion

This paper constructs option-implied interest rates for 10 of the G11 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.

REFERENCES

- Alyssa Anderson, Wenxin Du, and Bernd Schlusche. Arbitrage capital of global banks. Technical report, Working Paper University of Chicago, 2021.
- Stefan Avdjiev, Wenxin Du, Catherine Koch, and Hyun Song Shin. The dollar, bank leverage and deviations from covered interest rate parity. *American Economic Review: Insights, Forthcoming*, 1(2):193–208, 2019.
- Ben S Bernanke. Clearing and settlement during the crash. *The Review of Financial Studies*, 3(1):133–151, 1990.

- Wenxin Du, Joanne Im, and Jesse Schreger. The U.S. Treasury Premium. *Journal of International Economics*, 112:167–181, 2018a. ISSN 18730353. doi: 10.1016/j.jinteco.2018.01.001.
- Wenxin Du, Alexander Tepper, and Adrien Verdelhan. Deviations from covered interest rate parity. *The Journal of Finance*, 73(3):915–957, 2018b. doi: 10.1111/jofi.12620. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/jofi.12620>.
- Charles Engel and Steve Pak Yeung Wu. Liquidity and exchange rates: An empirical investigation. *Review of Economic Studies*, 2022.
- Zhiguo He, Stefan Nagel, and Zhaogang Song. Treasury inconvenience yields during the covid-19 crisis. *Journal of Financial Economics*, forthcoming, 2021.
- John Hicks. Mr. Keynes and the “classics”: a suggested interpretation. *Econometrica*, 5(2):147–159, 1937.
- Arvind Krishnamurthy and Annette Vissing-Jorgensen. The aggregate demand for Treasury debt. *Journal of Political Economy*, 120(2):233–267, 2012. ISSN 0022-3808. doi: 10.1086/666526.
- Gordon Liao. Credit migration and covered interest rate parity. *Journal of Financial Economics*, 138(2):504–525, 2020.
- Yiming Ma, Kairong Xiao, and Yao Zeng. Mutual fund liquidity transformation and reverse flight to liquidity. *Review of Financial Studies*, forthcoming, 2021.
- Stefan Nagel. The liquidity premium of near-money assets. *Quarterly Journal of Economics*, 131:1927–1971, 2016.
- Jules van Binsbergen, William Diamond, and Marco Grotteria. Risk-free interest rates. *Journal of Financial Economics*, forthcoming, 2021.

Appendix

A Model Derivations: Consumer's Problem

The consumer's consumption at time 2 is $c_{j2} = \frac{P_{jt}}{P_{j,t+1}}[C_{jt} + (1 + i_{d,jt})D_{jt}] + \sum_k w_{jk}\delta_{jk}$. Consumption at time 1 is $c_{j1} = W_j - C_{jt} - D_{jt} - \sum_k w_{jk}p_{jk}$. Plugging these budget constraints into the consumers utility function (equation 8) yields the objective function

$$\max_{D_{jt}, C_{jt}, w_{jk} \geq 0} u(W_j - C_{jt} - D_{jt} - \sum_k w_{jk}p_{jk}) + \quad (A1)$$

$$\beta E_t u'(C_{jt} \frac{P_{jt}}{P_{j,t+1}} + (1 + i_{d,jt})D_{jt} \frac{P_{jt}}{P_{j,t+1}} + \sum_k w_{jk}\delta_{jk}) + v(C_{jt}, D_{jt}). \quad (A2)$$

The Euler equations for all assets held in positive quantities are

$$p_{jk} = \frac{\beta E_t \delta_{jk} u'(c_{j,t+1})}{u'(c_{jt})} \quad (A3)$$

$$1 = (1 + i_{d,jt}) \frac{\beta E_t u'(c_{j,t+1})}{u'(c_{jt})} \frac{P_{jt}}{P_{j,t+1}} + \frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial D_{jt}}}{u'(c_{jt})} \quad (A4)$$

$$1 = \frac{\beta E_t u'(c_{j,t+1})}{u'(c_{jt})} \frac{P_{jt}}{P_{j,t+1}} + \frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial C_{jt}}}{u'(c_{jt})}. \quad (A5)$$

For a risk-free nominal asset that does not provide liquidity services, its interest rate i_{jt} satisfies

$$1 = (1 + i_{jt}) \frac{\beta E_t u'(c_{j,t+1})}{u'(c_{jt})} \frac{P_{jt}}{P_{j,t+1}}. \quad (A6)$$

Plugging equation A6 into equation A5 yields

$$1 = \frac{1}{1 + i_{jt}} + \frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial C_{jt}}}{u'(c_{jt})} \quad (\text{A7})$$

$$1 - \frac{1}{1 + i_{jt}} = \frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial C_{jt}}}{u'(c_{jt})}. \quad (\text{A8})$$

Using these expressions in equation A4 yields

$$1 = \frac{1 + i_{d,jt}}{1 + i_{jt}} + \left(1 - \frac{1}{1 + i_{jt}}\right) \frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial D_{jt}}}{\frac{\partial v(C_{jt}, D_{jt})}{\partial C_{jt}}} \quad (\text{A9})$$

$$i_{jt} - i_{d,jt} = i_{jt} \frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial D_{jt}}}{\frac{\partial v(C_{jt}, D_{jt})}{\partial C_{jt}}}. \quad (\text{A10})$$

This is precisely equation 10 from the main text.

B Model Derivations: Intermediary's problem

Suppose the intermediary's portfolio pays $\delta_{jt}^I = \sum w_{jk}^I \delta_{jk}$, and it has issued deposits D_{jt} . The intermediary makes a payout $\delta_{jt}^I - (1 + i_{d,jt})D_{jt} \frac{P_{jt}}{P_{j,t+1}}$ to equity and $(1 + i_{d,jt})D_{jt} \frac{P_{jt}}{P_{j,t+1}}$ to depositors. The household's consumption Euler equation (equation A3) implies that $E_{jt} = \frac{\beta E_t(\delta_{jt}^I - (1 + i_{d,jt})D_{jt} \frac{P_{jt}}{P_{j,t+1}})u'(c_{t+1})}{u'(c_t)}$, and the household's first order condition for deposits (equation A4) implies that $D_{jt} = \frac{\beta E_t((1 + i_{d,jt})D_{jt} \frac{P_{jt}}{P_{j,t+1}})u'(c_{t+1})}{u'(c_t)} + \frac{\frac{\partial v(C_t, D_t)}{\partial D_t}}{u'(c_t)} D_{jt}$. The intermediary's objective function is therefore

$$\frac{\beta E_t(\sum w_{jk}^I \delta_{jk} - (1 + i_{d,jt})D_{jt} \frac{P_{jt}}{P_{j,t+1}})u'(c_{t+1})}{u'(c_t)} + \frac{\beta E_t((1 + i_{d,jt})D_{jt} \frac{P_{jt}}{P_{j,t+1}})u'(c_{t+1})}{u'(c_t)} + \frac{\frac{\partial v(C_t, D_t)}{\partial D_t}}{u'(c_t)} D_{jt} - \sum w_{jk}^I p_{jk} \quad (\text{A11})$$

which the intermediary maximizes over its portfolio weights w_{jk}^I and the deposit quantity D_{jt} subject to the regulatory constraint $f(w_j^I) - D_{jt} \geq 0$. Holding fixed the intermediary's portfolio, its objective is increasing in D_{jt} , so it will issue deposits up to the regulatory

constraint. The intermediary's objection function equals

$$\max_{w_{jk}^I} \frac{\beta E_t(\sum w_{jk}^I \delta_{jk}) u'(c_{j,t+1})}{u'(c_{jt})} + \frac{\frac{\partial v(C_t, D_t)}{\partial D_t}}{u'(c_t)} f(w_j^I) - \sum w_{jk}^I p_{jk} \quad (\text{A12})$$

The intermediary's willingness to pay for an asset that pays dividend δ_{jk} is

$$\frac{\beta E_t u'(c_{j,t+1}) \delta_{jk}}{u(c_{jt})} + \frac{\partial f}{\partial w_{jk}} \frac{\frac{\partial v(C_t, D_t)}{\partial D_t}}{u'(c_t)} \quad (\text{A13})$$

If this is a risk-free asset that pays $1 + i_{jk}$ and hence costs 1, then by equations A4 and A6, we have that $\frac{\beta E_t u'(c_{j,t+1})}{u(c_{jt})} = (1 + i_{jk}) \beta E_t [\frac{u'(c_{j,t+1})}{u(c_{jt})} \frac{P_{jt}}{P_{j,t+1}}] = \frac{1+i_{jk}}{1+i_{jt}}$ and $\frac{\frac{\partial v(C_{jt}, D_{jt})}{\partial D_{jt}}}{u'(c_{jt})} = 1 - \frac{1+i_{d,jt}}{1+i_{jt}}$, so

$$1 = \frac{1 + i_{jk}}{1 + i_{jt}} + \frac{\partial f}{\partial w_{jk}} \frac{(i_{jt} - i_{d,jt})}{1 + i_{jt}} \quad (\text{A14})$$

$$i_{jt} - i_{jk} = \frac{\partial f}{\partial w_{jk}} (i_{jt} - i_{d,jt}), \quad (\text{A15})$$

which is equation 15 in the main text.

C Appendix: Counterparty Risk in Options Markets

The interest rates that we estimate are only risk-free to the extent that there is no meaningful credit risk in the equity options that we consider. We believe that credit risk is unlikely to impact our estimates. The first line of defense is that all investors must post marginal collateral for their options trades. After this, options exchanges themselves are liable for the contracts traded on them. Finally, an option clearing corporation, which is likely to be supported by a country's central bank in periods of distress, provides the final line of defense. All of the quotes we examine are from exchanges that are backed by a clearing house that meets the international standards and Principles for Financial Market Infrastructures (PFMIs). Table A1 lists the exchanges and clearing houses for the equity options that we consider. The PFMIs were introduced in 2012 by the Committee on Payments and Market Infrastructures (CPMI) of the Bank for International Settlements (BIS)

and by the Technical Committee of the International Organization of Securities Commissions (IOSCO). In the US and Europe, the Dodd-Frank Act and the European Markets Infrastructure Regulation stipulate that the national regulatory agencies take into consideration the international standards and PFMI when regulating systematically important central counterparties (CCPs). The goal of the PFMI is to reduce taxpayer risk and provide protections for cross-border clearing on CCPs even when the financial institutions doing the trading are located in different countries.

The result of adopting the PFMI is that there are several common layers of protection for systematically important CCPs that mitigate against potential losses from the default of a clearing member.³ First, there are rigorous standards to become a clearing member, so that default occurrences should be rare events to begin with. The key advantage of the CCP is then its ability to net positions across traders to reduce counterparty risk compared to bilateral exposures in the over-the-counter market. The exchange then imposes margin requirements against positions that are adjusted dynamically over time. In the event that a clearing member defaults and the margin collateral is insufficient to cover their losses on the exchange, the clearing house may then call upon the default fund. Default funds are pre-funded by all clearing members with enough capital to withstand the failure of at least two clearing members that create the greatest uncollateralized losses under stress scenarios. Contributions to the default funds are updated on a regular basis, such as monthly, to account for changes in market risks. In the unlikely event that the default fund is exhausted, the clearing house equity capital and that of its parent company are often applied to cover any remaining losses.⁴ Finally, almost all of the clearing houses considered in this paper are designated as “Systematically Important Financial Market Utilities” (SIFMUs) by their relevant national regulatory agencies and central banks. The SIFMU designation suggests

³Historical examples of clearing member defaults include Drexel Burnahm (1990), Woodhouse, Drake & Carey (1991), Barings (1995), Griffin (1998), Refco (2005), Lehman Brothers (2008), and MF Global (2011).

⁴The clearing houses considered in our paper have strong credit ratings. For example, the OCC is AA-rated, the parent company of Eurex Clearing is Deutsche Bourse AG which is AA-rated and has issued a letter of comfort in favor of providing Eurex Clearing with financial funding to comply with its obligations, and the parent company of ICE Clear Europe is Intercontinental Exchange Inc. (ICE) which is A-rated.

Option Exchanges and Clearing Houses

| Currency | Index Options | Exchange | Clearing House |
|----------|---------------|-------------------|---|
| USD | S&P 500 | CBOE | Options Clearing Corporation |
| EUR | Euro Stoxx 50 | Eurex | Eurex Clearing |
| CHF | SMI | Eurex | Eurex Clearing |
| GBP | FTSE 100 | ICE | ICE Clear Europe |
| SEK | OMXS30 | Nasdaq OMX Nordic | Nasdaq OMX Clearing |
| NOK | OMXO20 | Nasdaq OMX Nordic | Nasdaq OMX Clearing |
| DKK | OMXC25 | Nasdaq OMX Nordic | Nasdaq OMX Clearing |
| CAD | TSX 60 | Montreal Exchange | Canadian Derivatives Clearing Corporation |
| AUD | ASX 200 | ASX | ASX Clear |
| JPY | Nikkei 225 | Osaka Exchange | Japan Securities Clearing Corporation |

Table A1. Option exchange and clearing house where the index options are traded for each currency.

that their may be further implicit support from the regulatory sector in the event that the exchange's default waterfall protections including position netting, margin, the default fund, and the clearing house equity capital contributions are insufficient to cover losses.⁵

D Appendix: Additional Tables and Figures

⁵For example, during the 1987 stock market crash, the Federal Reserve intervened to ensure that all derivative contracts were paid off (Bernanke, 1990). Examples of the agencies and central banks that regulate the clearing houses that we consider include the SEC, CFTC, Federal Financial Supervisory Authority (Germany), Swiss National Bank, Swiss Financial Market Supervisory Authority, Bank of England, Bank of Japan, Swedish Financial Supervisory Authority, Norwegian Ministry of Finance, Bank of Canada, and Royal Bank of Australia.

Table A2

| Variable | Coefficient | Standard Error | Coefficient | Standard Error |
|-----------------------|--------------------|----------------|------------------|----------------|
| $\Delta BoxCIP_{j,t}$ | - 7.384354 | 1.922398 | - 8.832989 | 1.871208 |
| $BoxCIP_{j,t-1}$ | - .7242225 | .8486421 | - 2.200316 | .8253527 |
| $\Delta CYdiff_{j,t}$ | -3.571914 | 1.997259 | -3.369753 | 1.94568 |
| $CYdiff_{j,t-1}$ | - .7152574 | 1.259807 | -1.635154 | 1.227618 |
| R-squared: | 0.0743 | | 0.1210 | |
| Predicted variable | $\Delta s_{j,t+1}$ | | $\Delta s_{j,t}$ | |
| Country | Euro | | Euro | |

| Variable | Coefficient | Standard Error | Coefficient | Standard Error |
|-----------------------|--------------------|----------------|------------------|----------------|
| $\Delta BoxCIP_{j,t}$ | - 3.927983 | 1.922398 | - 1.650959 | 1.370271 |
| $BoxCIP_{j,t-1}$ | - .3656888 | .8486421 | - .8922766 | .6264158 |
| $\Delta CYdiff_{j,t}$ | -3.702692 | 1.997259 | -3.856876 | 1.518397 |
| $CYdiff_{j,t-1}$ | - .2230881 | 1.259807 | 1.669026 | .9699831 |
| R-squared: | 0.0455 | | 0.0402 | |
| Predicted variable | $\Delta s_{j,t+1}$ | | $\Delta s_{j,t}$ | |
| Country | Switzerland | | Switzerland | |

| Variable | Coefficient | Standard Error | Coefficient | Standard Error |
|-----------------------|--------------------|----------------|------------------|----------------|
| $\Delta BoxCIP_{j,t}$ | - 5.810349 | 2.454897 | - 7.162113 | 2.373918 |
| $BoxCIP_{j,t-1}$ | -2.926835 | 1.069485 | - 3.995262 | 1.034009 |
| $\Delta CYdiff_{j,t}$ | -5.089251 | 2.459937 | -5.527515 | 2.379199 |
| $CYdiff_{j,t-1}$ | -3.514129 | 1.354011 | -4.267241 | 1.309607 |
| R-squared: | 0.0669 | | 0.1119 | |
| Predicted variable | $\Delta s_{j,t+1}$ | | $\Delta s_{j,t}$ | |
| Country | UK | | UK | |

Monthly Exchange Rate Forecast Regressions, following Engel and Wu (2022), separately by country. Monthly regression from Jan 2004 to July 2020.

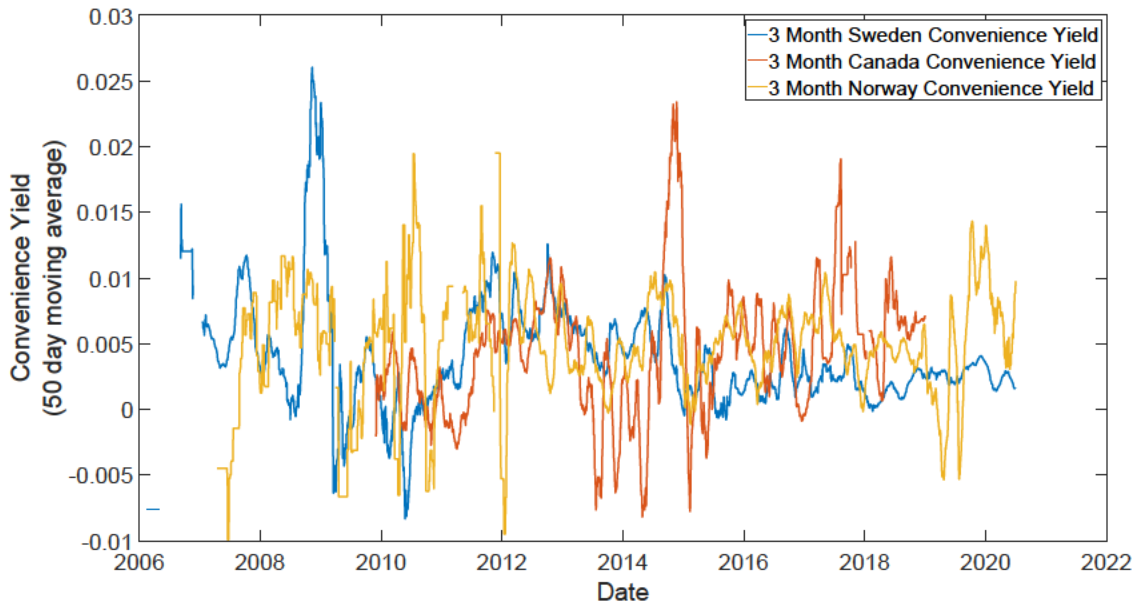


Figure A1. Three-Month Convenience Yields, Measured as One-Year Box Rates Minus One-Year Government Yields, for Sweden, Norway, and Canada.

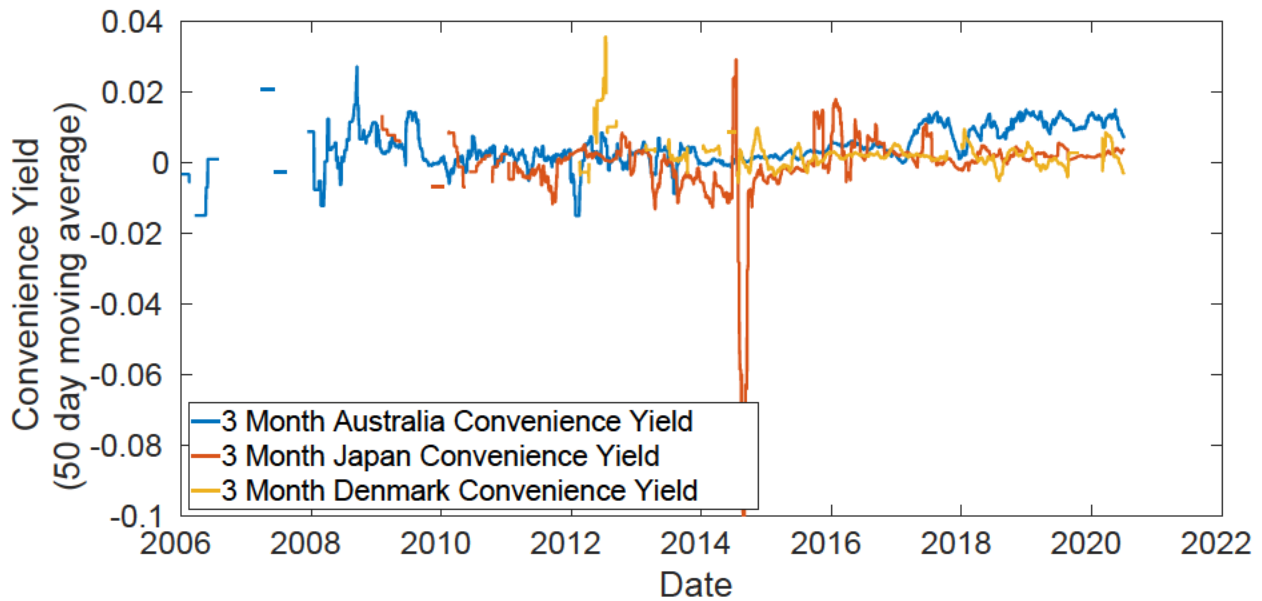


Figure A2. Three-Month Convenience Yields, Measured as One-Year Box Rates Minus One-Year Government Yields, for Australia, Denmark, and Japan.