# Foreign Safe Asset Demand for U.S. Treasurys and the Dollar*

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**Abstract**

The convenience yield that foreign investors derive from holding U.S. Treasurys causes a failure of Covered Interest Rate Parity by driving a wedge between the yield on the foreign bonds and the currency-hedged yield on the U.S. Treasury bonds. Even before the 2007-2009 financial crisis, the Treasury-based dollar basis is negative and occasionally large. We use the Treasury basis as a measure of the foreign convenience yield. Consistent with the theory, an increase in the convenience yield that foreign investors impute to U.S. Treasurys coincides with an immediate appreciation of the dollar, but predicts future depreciation of the dollar. The Treasury basis variation accounts for up to 25% of the quarterly variation in the dollar between 1988 and 2017.

*Keywords*: Covered Interest Rate Parity, exchange rates, safe asset demand, convenience yields.

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During episodes of global financial instability, there is a flight to the safety of U.S. Treasury bonds which increases their convenience yield, the non-pecuniary value that investors impute to the safety and liquidity properties of U.S. Treasury bonds (see Krishnamurthy and Vissing-Jorgensen, 2012, for example). Figure 1 illustrates this pattern for the 2008 financial crisis. The blue line is the spread between 12-month USD LIBOR and 12-month U.S. Treasury bond yields (TED spread), which is a measure of the convenience yield on U.S. Treasury bonds. The spread roughly triples in the flight to safety of the fall of 2008. We also graph the U.S. dollar exchange rate (green), measured against a basket of other currencies as well as the U.S. dollar currency basis (red), which we will define shortly. The dollar appreciates by about 30% over this period. The hypothesis of this paper is that the increase in the convenience yield on U.S. Treasury bonds assigned by foreign investors will also be reflected in an appreciation of the U.S. dollar. The spot exchange rate of a safe asset currency will reflect the value of all future convenience yields.

Our theory rests on the premise that U.S. Treasury bonds are an international safe asset and that investors pay a premium to own these assets. There is a growing body of literature in support of this premise and the key role of the U.S. as a world safe asset supplier (see Caballero, Farhi, and Gourinchas, 2008; Caballero and Krishnamurthy, 2009; Maggiori, 2017; He, Krishnamurthy, and Milbradt, 2017). The next section develops the theory to link movements in the convenience yield to movements in the U.S. dollar exchange rate. We then provide systematic evidence, beyond Figure 1, in support of the theory. We show that our Treasury-based measure of CIP deviations, the Treasury basis, behaves differently from the Libor basis that is studied by Ivashina, Scharfstein, and Stein (2015) during the Eurozone crisis, and Du, Tepper, and Verdelhan (2017) in their recent influential paper dissecting the breakdown in the LIBOR CIP condition post-crisis.[1]

[1] Amador, Bianchi, Bocola, and Perri (2017) attribute CIP deviations to exchange rate management by central banks at the zero lower bound.

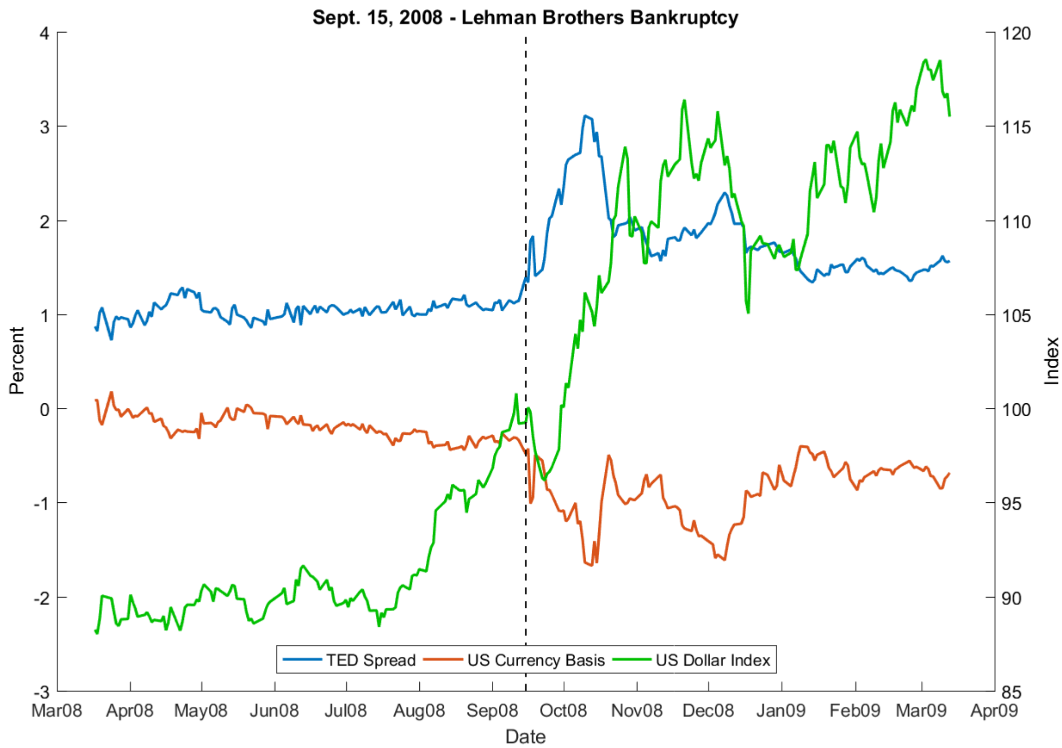


Figure 1: TED Spread, Average Treasury Basis and Dollar.

# 1 A Simple Model of Spot Exchange Rates, Forward Exchange Rates and Convenience Yields on U.S. Treasury Bonds.

There are two countries, foreign ($*$) and the U.S. ($), each with its own currency. Denote $S_t$ as the nominal exchange rate between these countries, where $S_t$ is expressed in units of foreign currency per dollar so that an increase in $S_t$ corresponds to an appreciation of the U.S. dollar. There are domestic (foreign) nominal government bonds denominated in dollars (foreign currency).

We derive bond pricing conditions that must be satisfied in asset market equilibrium. We consider the case of risk-neutrality in this section. We develop pricing expressions for the more standard case with SDFs in section B of the Appendix.

Foreign investors price foreign bonds denominate in foreign currency, and the foreign investor's Euler equation is given by:

$$E_t[e^{-\rho_t^*} e^{y_t^*}] = 1, \tag{1}$$

where $e^{-\rho_t^*}$ is the one-period nominal stochastic discount factor for payoffs in foreign currency in our model and $y_t^*$ denotes the yield on the foreign currency denominated bonds. As noted, we assume that investors are risk-neutral: $\rho_t^*$ is known at time $t$, i.e., non-stochastic so that one can drop the expectation operator in equation (1), which implies that the foreign bond yield equals the investor's discount rate

$$y_t^* = \rho_t^*.$$

## 1.1 Foreign Demand for U.S. Treasurys

Foreign investors can also invest in U.S. Treasurys. To do so, they convert local currency to U.S. dollars to receive $\frac{1}{S_t}$ dollars, invest in U.S. Treasurys, and then convert the proceeds back to local currency at date $t+1$ at $S_{t+1}$. Then,

$$E_t\left[e^{-\rho_t^*} \frac{S_{t+1}}{S_t} e^{y_t^\$}\right] = e^{-\lambda_t^*}, \qquad \lambda_t^* \geq 0. \tag{2}$$

The expression on the left side of the equation is standard. On the right side, we allow investors in U.S. Treasurys to derive a convenience yield, $\lambda_t^*$, on their Treasury bond holdings. If the convenience yield rises, lowering the right side of the equation, the required return on the investment in U.S. Treasury bonds (the left side of the equation) falls; either the expected rate of dollar depreciation declines or the yield $y_t^\$$ declines, or both.

Consider the U.S. investor next. The U.S. investors also derive a convenience yield when investing in U.S. Treasurys. Hence, a U.S. investor faces the following Euler equation:

$$E_t[e^{-\rho_t^\$} e^{y_t^\$}] = e^{-\lambda_t^\$}, \qquad \lambda_t^\$ \geq 0. \tag{3}$$

Again we assume that the discount factor is deterministic so that,

$$y_t^\$ = \rho_t^\$ - \lambda_t^\$, \tag{4}$$

i.e, U.S. Treasury bond yields are lowered by the U.S. investor's convenience yield.

Next, we next use these pricing conditions to derive an expression linking the exchange rate and the convenience yield. We combine equations (1) and (2) to derive the following relation for the exchange rate today:

$$0 = \lambda_t^* + (y_t^\$ - y_t^*) + E_t[\Delta s_{t+1}] + \frac{1}{2} var[\Delta s_{t+1}] \tag{5}$$

where $s_t \equiv \ln\ S_t$ is the log exchange rate, and we have assumed log-normality.[2] To keep the analysis simple, we assume the variance is constant. When $\lambda_t^* = 0$, this equation is the textbook U.I.P. condition: the dollar's expected rate of appreciation equals the yield difference $(y_t^* - y_t^\$)$ minus a small Jensen's adjustment.[3] The convenience yield of foreign investors drives a wedge in the UIP condition causing the dollar to appreciate today, at $t$, as previously pointed out by Valchev (2016).

Where does the U.S. investor's convenience demand for U.S. bonds go? The yield on U.S. Treasuries $y_t^\$$ adjusts directly to reflect the U.S. investor's convenience yield, as in (4), and hence enters the U.I.P. condition through the U.S. Treasury yield. Note that if $\lambda_t^\$$ equals $\lambda_t^*$, then eqn. (5) reduces to the standard U.I.P. condition:

$$0 = (\rho_t^\$ - \rho_t^*) + E_t[\Delta s_{t+1}] + \frac{1}{2} var[\Delta s_{t+1}], \tag{6}$$

which does not depend on the convenience yields. Only the gap in convenience yields matters for exchange rate dynamics.

To provide evidence for our convenience yield theory, we work with two versions of equation (5). First, equation (5) is a forecasting regression:

$$E_t[s_{t+1}] = s_t - \lambda_t^* - (y_t^\$ - y_t^*) - \frac{1}{2} var[\Delta s_{t+1}]$$

[2] If we do not assume log-normality, the last variance term is replaced by $L_t(s_{t+1})$, the conditional entropy of the exchange rates.

[3] Since investors are risk-neutral, U.I.P. holds by construction, and the log currency risk premium on a long position in dollars $rp_{t+j}^{FX} = (y_t^\$ - y_t^*) + E_t[\Delta s_{t+1}] = -\frac{1}{2} var(\Delta s_{t+j})$. This being the case, the expected excess return in levels is zero.

We will verify the relation between the convenience yield and the future exchange rate in the data. Again, the variance term is a constant here. Second, we iterate forward on equation (5) to write,

$$s_t = constant + E_t\left[\sum_{\tau=0}^{\infty}\lambda^*_{t+\tau}\right] + E_t\left[\sum_{\tau=0}^{\infty}(y^{\$}_{t+\tau} - y^*_{t+\tau})\right] + E_t[\lim_{j\to\infty} s_{j+t}], \tag{7}$$

where the constant is a sum of the variance terms. The last term is constant under the assumption that the exchange rate is stationary. The exchange rate level is determined by yield differences and the convenience yields. This is an extension of Froot and Ramadorai (2005)'s expression for the level of exchange rates. The first term involves the sum of expected convenience yields on the U.S. Treasurys. The second term involves the sum of bond yield differences. This expression implies that changes in the expected future convenience yields should drive changes in the dollar exchange rate. Section B of the Appendix derives a more general expression for the log of the exchange rate that allows for risk premia (see proposition 3):

$$s_t = E_t\sum_{\tau=0}^{\infty}\lambda^*_{t+\tau} + E_t\sum_{\tau=0}^{\infty}(y^{\$}_{t+\tau} - y^*_{t+\tau}) - E_t\sum_{\tau=0}^{\infty} rp^{FX}_{t+j} + \bar{s}$$

where $rp^{FX}_t$ is the log risk premium on a long position in dollars, and we assumed the foreign investor derives no convenience yields from the foreign bond. Under risk-neutrality, $rp^{FX}_{t+j} = -\frac{1}{2}var(\Delta s_{t+j})$.

### 1.2 U.S. Demand for Foreign Bonds

What about the returns on foreign bonds? If U.S. investors have access to foreign bond markets, then there is another Euler equation to consider.[4] To keep the analysis simple, assume that foreign bonds produce no convenience yields for either US or foreign investors. Then, an increase in the foreign convenience yield imputed to U.S. Treasurys leads to an excess return to US

[4] In this risk-neutral case, the U.S. investor's Euler equation for the foreign bond cannot hold while the U.S. investor's Euler equation in eqn. (2) also holds –with zero convenience yields: The foreign investor and the home investor cannot both earn zero excess returns on long positions in the other country's bonds. This is referred to as Siegel's paradox (see section A of the appendix). In the general SDF case, all Euler equations can hold with equality, because of the currency risk premia.

investors in foreign bonds:

$$E_t\left[e^{-\rho_t^{\$}}\frac{S_t}{S_{t+1}}e^{y_t^*}\right] > 1. \tag{8}$$

If $\lambda_t^*$ rises, the dollar appreciates immediately and is expected to depreciate over time. For a U.S. investor, buying foreign bonds when the dollar is expected to depreciate produces a high carry return.

How can the U.S. Euler equation for foreign bonds hold in equilibrium? There are two ways this may happen. First, in the general SDF case, the risk premium that U.S. investors expect on a long position in foreign bonds should then increase, thus restoring the Euler equality. This is a natural equilibrium outcome given that U.S. investors would increase their exposure to FX risk via the foreign bond carry trade. In section A of the appendix, we derive the following restriction on the convenience yields:

$$\lambda_t^* - \lambda_t^{\$} = RP_t^{\$,*} - RP_t^{*,\$} - var_t[\Delta s_{t+1}].$$

An increase in $\lambda_t^*$ would then be accompanied by a proportional increase in the risk premium U.S. investors demand on foreign bonds ($RP_t^{\$,*}$).

A second possibility is frictions in financial intermediation. Suppose that the Euler equation in (8) applies to a financial intermediary that is subject to capital constraints as in intermediary asset pricing models. Then, the Lagrange multiplier on this constraint will enter the Euler equation, so that a binding constraint can also restore equilibrium. The evidence from Du, Tepper, and Verdelhan (2017) is consistent with this frictional mechanism.

For the purposes of the present analysis, we do not take a stand on the U.S. Euler equation. We know that there are theoretically coherent ways to specify this equation, and given that, we focus on the model's predictions for foreign investors' convenience demand and the dollar exchange rate.

## 2 Empirical Analysis of Exchange Rates, Treasury Basis, and Convenience Yields

We use quarterly data from 10 developed economies. The countries are Australia, Canada, Germany, Japan, New Zealand, Norway, Sweden, Switzerland, United States, and United Kingdom. The sample starts in 1988Q1 and ends in 2017Q2. However, the panel is unbalanced, with data for only a few countries at the start of the sample. The data comprises the bilateral exchange rates with respect to the U.S. dollar, 12-month bilateral forward foreign exchange contract prices, and 12-month government bond yields and LIBOR rates in all countries. We do usual actual rather than fitted yields for government bonds whenever possible. The main exception is the 2001:9-2008:5 period when the U.S. stopped issuing 12-month bills.[5]

### 2.1 Treasury-based Currency Basis

The key data construction is the "basis," which we use to measure $\lambda_t^*$. A positive foreign convenience yield for U.S. Treasuries leads U.I.P. to fail and can also lead C.I.P. to fail. To see why, consider a currency hedged investment in the U.S. Treasury. Naturally, this investment also produces a convenience yield for foreign investors, denoted $\lambda_t^{*,hedged}$. The corresponding Euler equation is given by:

$$E_t\left[e^{-\rho_t^*}\frac{F_t^1}{S_t}e^{y_t^\$}\right] = e^{-\lambda_t^{*,hedged}}, \qquad \lambda_t^{*,hedged} \geq 0, \tag{9}$$

where $F_t^1$ denotes the one-year forward exchange rate, expressed in units of foreign currency per dollar. We combine this equation with (1) to derive the Treasury-based dollar basis:

$$x_t \equiv y_t^\$ + (f_t^1 - s_t) - y_t^* = -\lambda_t^{*,hedged}. \tag{10}$$

Here, $x_t$ is the dollar basis, or violation of the C.I.P. condition (see Du, Tepper, and Verdelhan, 2017). In a world without foreign convenience yields, the basis is zero, but, when $\lambda_t^{*,hedged} > 0$,

[5] See Table 3 in the Appendix for detailed information. The Data Appendix contains information about data sources.

foreign investors accept a lower return on hedged investments in U.S. Treasury bonds than in their home bonds. This drives a wedge between the currency-hedged Treasury yield $y_t^{\$}+(f_t^1-s_t)$ and the foreign currency yield $y_t^*$ and hence causes a negative Treasury basis $x_t < 0$.[6]

We posit that the convenience yields on the unhedged and hedged investments are proportional to each other,

$$\frac{\lambda_t^*}{\lambda_t^{*,hedged}} = \phi_t \Rightarrow \lambda_t^* = \phi_t \lambda_t^{*,hedged} = -\phi_t x_t$$

so that we rewrite (5) as,

$$s_t = -\phi_t x_t + (y_t^{\$} - y_t^*) + E_t[s_{t+1}] + \frac{1}{2} var(s_{t+1}), \tag{11}$$

and,

$$s_t = constant - E_t\left[\phi \sum_{\tau=1}^{\infty} x_\tau\right] + E_t\left[\sum_{\tau=1}^{\infty}(y_\tau^{\$} - y_\tau^*)\right] + E_t[\lim_{j\to\infty} s_{t+j}]. \tag{12}$$

We construct the basis for each currency following (10). We do so using both government bond yields as measures of $y_t$ as well as LIBOR rates as measures ($x^{Treasury}$ and $x^{LIBOR}$). In each quarter, we construct the mean and median basis across the panel of countries for that quarter. Figure 2 plots these series.

The blue thick-dashed line corresponds to the median LIBOR basis.[7] That basis is close to zero for most of the sample and turns negative and volatile beginning in 2007. These facts concerning the LIBOR basis are known from the work of Du, Tepper, and Verdelhan (2017). The solid black line is the mean Treasury basis (the dashed black line is the median Treasury basis). *Unlike the LIBOR basis, the Treasury basis has always been negative and volatile.* The standard deviation of the Treasury basis is 24 bps per quarter.

[6] This result about the connection between Treasury-based CIP violations and convenience yields was pointed out by Adrien Verdelhan in a discussion at the Macro Finance Society (2017).

[7] The dotted blue-line is the mean LIBOR basis. This series is not informative pre-crisis because its spikes are driven by idiosyncracies of LIBOR rates in Sweden in 1992 and Japan in 1995.

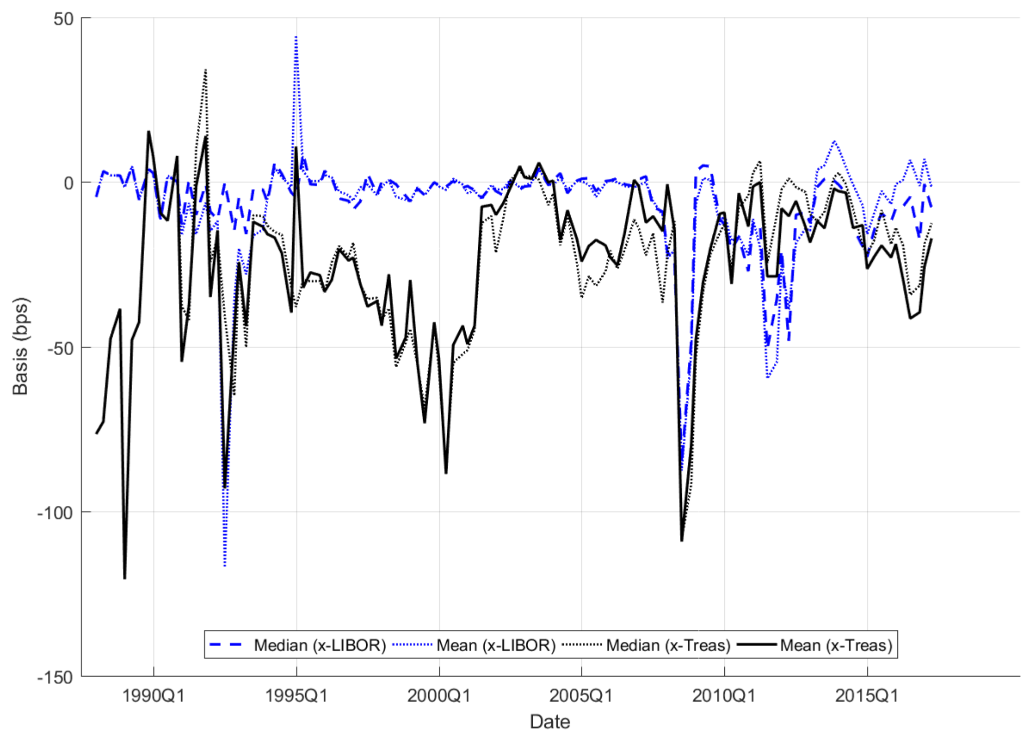


Figure 2: LIBOR and Treasury basis in basis points from 1988Q1 to 2017Q2. The maturity is one year.

## 2.2 The Treasury Basis and the Dollar

We denote the cross-sectional mean basis as $\overline{x}_t^{Treas}$. Similarly, we use $\overline{y}_t^* - y_t^\$$ to denote the cross-sectional average of yield differences, and $\overline{s}_t$ denotes the equally weighted cross-sectional average of the log of bilateral exchange rates against the dollar. For each of these cross-sectional averages, we employ the same set of countries that are in the sample at time $t$. The average Treasury basis is negatively correlated ($-0.27$) with the average interest rate difference $\overline{y}_t^* - y_t^\$$.

We construct quarterly innovations in the basis by regressing $\overline{x}_t^{Treas} - \overline{x}_{t-1}^{Treas}$ on $\overline{x}_{t-1}^{Treas}$ and $\overline{y}_{t-1}^* - y_{t-1}^\$$ and computing the residual, $\Delta\overline{x}_t^{Treas}$. We then regress this innovation on the contemporaneous quarterly change in the spot exchange rate, $\Delta\overline{s}_t \equiv \overline{s}_t - \overline{s}_{t-1}$, Table 1 reports the results. From columns (1), (3), (4), and (6), we see that the innovation in the Treasury basis strongly correlates with changes in the exchange rate. The sign is negative as expected.

The result is also stable across the pre-crisis and post-crisis sample. A 10 bps decrease in the basis (or an increase in the foreign convenience yield) above its mean coincides with a 3.9% appreciation of the U.S. dollar. These effects account for 18.2% to 25.9% of the variation in the dollar's rate of appreciation.

The $R^2$s are quite high for exchanges rates, i.e. in light of the well-known exchange rate disconnect puzzle (Froot and Rogoff, 1995; Frankel and Rose, 1995). The LIBOR basis has explanatory power in the post-crisis sample as has been documented in prior work by Avdjiev, Du, Koch, and Shin (2016). They attribute this effect to an increase in the supply of dollars after a dollar depreciation by a foreign banking sector that borrows heavily in dollars. However, in the full sample and the pre-crisis sample there is no relation between the LIBOR basis and the appreciation of the dollar. Even in the post-crisis sample, the Treasury basis doubles the explanatory power.

Table 1: Average Treasury Basis and Changes in the USD Spot Exchange Rate

The dependent variable is the (annualized) quarterly change in the log of the spot USD exchange rate against a basket. The independent variables are the innovation in the average Treasury basis, $\Delta\overline{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation, and the innovation in the LIBOR basis. Data is quarterly. OLS standard errors in parentheses.

| | 1988Q1−2017Q2 | | | 1988Q1−2007Q4 | | 2008Q1−2017Q2 | |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| $\Delta\overline{x}^{Treas}$ | $-39.8^{***}$ | | $-40.1^{***}$ | $-35.6^{***}$ | | $-52.1^{***}$ | |
| | (7.9) | | (7.6) | (9.9) | | (12.4) | |
| Lag $\Delta\overline{x}^{Treas}$ | | | $-24.7^{***}$ | | | | |
| | | | (7.6) | | | | |
| $\Delta\overline{x}^{LIBOR}$ | | $-11.7$ | | | 9.2 | | $-39.8^{***}$ |
| | | (12.0) | | | (16.5) | | (15.6) |
| $R^2$ | 18.2% | 0.0 | 25.9 | 14.3 | 0.0 | 33.5 | 15.7 |
| N | 116 | 116 | 116 | 79 | 79 | 37 | 37 |

Column (3) of Table 1 includes the contemporaneous and the lagged innovation to the basis. This specification provides the best fit in the table with an $R^2$ of 25.9%. The explanatory power of the lag is somewhat surprising and is certainly not consistent with our model as it indicates that there is a delayed adjustment of the exchange rate to shocks to the basis. On the other hand, time-series momentum has been shown to be a common phenomena in many asset markets, including currency markets (see Moskowitz, Ooi, and Pedersen, 2012), although there is no commonly agreed explanation for such phenomena.

We turn to the second implication of equation (11), which can also be read as a forecasting regression. Rewrite equation (11) as,

$$(E_t[\overline{s}_{t+1}] - \overline{s}_t) + (y_t^{\$} - \overline{y}_t^*) = constant + \phi_t \overline{x}_t \tag{13}$$

A more negative $x_t$ (high $\lambda^*$) today means that today's exchange rate appreciates, which induces an expected depreciation over the next period.

Note that the LHS of equation (13) is akin to the return on the reverse currency carry trade. It involves going long the U.S. Treasury bond, funded by borrowing at the rate of the foreign government bond. The carry trade return has a risk premium, and following the literature, a proxy for this risk premium is the yield differential across the countries, $y^{\$} - \overline{y}^*$. Thus we include the mean yield differential at each date as a control in our regression. Additionally as we have shown in Table 1, there is a slow adjustment to basis shocks, as given by the lag of $\Delta\overline{x}_t^{Treas}$, which we also include in our regression. Our regression specification is,

$$(\overline{s}_{t+1} - \overline{s}_t) + (y_t^{\$} - \overline{y}_t^*) = \alpha + \beta_x \overline{x}_t^{Treas} + \beta_y (y^{\$} - \overline{y}^*) + \beta_L \Delta\overline{x}_{t-1}^{Treas} + \epsilon_{t+1}$$

Our theory suggests that the coefficient $\beta_x$ should be positive. We run this regression using quarterly data, but compute the returns on the LHS as one-year, two-year, and three-year returns. Because there is overlap in the observations, we compute Newey-West standard errors.

Table 2 presents the results. The coefficient on $\overline{x}^{Treas}$ is positive as suggested by our theory, but the evidence is weak, and $\beta_x$ is only significantly different from zero in the 3-year specification. If we exclude the average Treasury currency basis from this specification, the $R^2$ drops to 6%. However, note that even the known predictor of carry trade returns, $y^{\$} - \overline{y}^*$, is only significant in the 3-year specification. Our returns specification suffers from a problem of power.

Table 2: Predicting Currency Excess Returns

The dependent variable is the annualized excess return on a long position in U.S. Treasuries and a short position (equal-weighted) in all foreign bonds, $(\overline{s}_{t+1} - \overline{s}_t) + (y_t^{\$} - \overline{y}_t^*)$, in units of log yield (i.e., 5% is 0.05). The independent variables are the average Treasury basis, $\overline{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation in the average Treasury basis, and the average yield difference $(y^{\$} - \overline{y}^*)$ in units of log yield. Data is quarterly from 1988Q1 to 2017Q2. Newey-West standard errors in parentheses.

| | 1-year | 2-year | 3-year |
|---|---|---|---|
| $\overline{x}^{Treas}$ | 7.1 | 10.0 | 21.0$^{***}$ |
| | (13.1) | (7.2) | (8.2) |
| $y^{\$} - \overline{y}^*$ | 0.65 | 0.78 | 1.56$^{***}$ |
| | (1.02) | (0.70) | (0.72) |
| Lag $\Delta\overline{x}^{Treas}$ | −16.1 | −13.3$^{***}$ | −22.4$^{***}$ |
| | (10.3) | (5.4) | (6.4) |
| $R^2$ | 5.0% | 5.5 | 14.1 |
| N | 112 | 108 | 104 |

In our other work (Krishnamurthy, Lustig, and Jiang, 2017), we study the entire cross-section of bilateral carry trade returns. In that case, there is more power and we are able to reject the null of no-convenience yield effects. This evidence suggests that convenience yields may partly account for the profitability of the dollar carry trade (Lustig, Roussanov, and Verdelhan, 2014), which goes long in a basket of foreign currencies and shorts the dollar when the average interest rate difference increases, and the Treasury basis widens.

The magnitude of $\beta_x$ is about 10 times larger than the magnitude of $\beta_y$ indicating that the basis, although small, has a sizable effect on exchange rates. A 10 bps. widening of the basis (i.e. the basis turns more negative) reduces the expected excess return on a long position in U.S. bonds by 2.1 % per annum over the next three years.

We use a Vector Autoregression to get a better sense of the joint dynamics of the interest rate difference, the exchange rate and the Treasury basis. We run a VAR with three variables, $\overline{x}_t^{Treas}$, $y_t^{\$} - \overline{y}_t^*$, and $\overline{s}_t$. The VAR includes one lag of all variables. This specification assumes that the log of the dollar index is stationary, which seems to be case in this sample period. We order the VAR so that shocks to the basis affect all variables contemporaneously, shocks to interest rate differentials affects the exchange rate but not the basis, and shocks to the exchange rate only affect itself. Figure 3 plots the impulse response from orthogonalized shocks to the basis. The left panel plots the dynamic behavior of the basis (in units of basis points) and the right panel plots the dynamic behavior of the exchange rate (in log points). The pattern in the figure is consistent with the regression evidence from the Tables. An increase in the basis of 20 basis points (decrease in the convenience yield) depreciates the exchange rate contemporaneously by about 3% over two quarters. The finding that the depreciation persists over 2 quarters is consistent with the time-series momentum effect discussed earlier. Then there is a gradual reversal out two to three years over which the effect on the level of the dollar gradually dissipates.

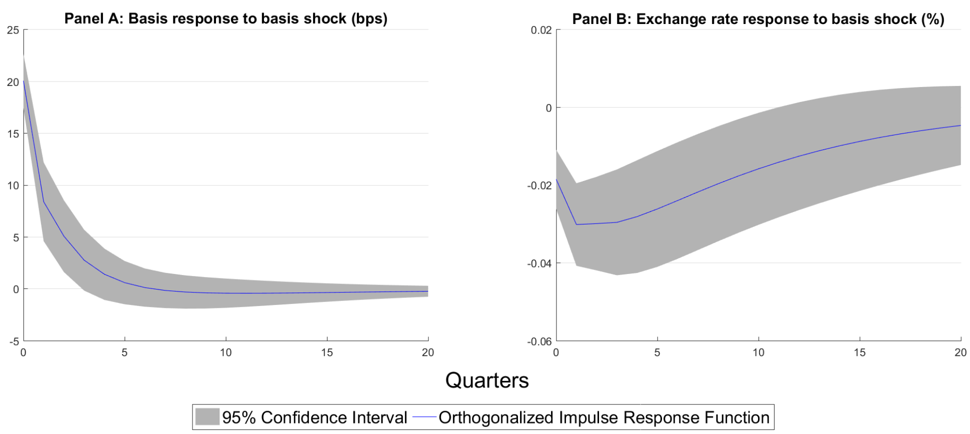


Figure 3: Impulse Response to an Average Treasury Basis Shock

The blue line plots the impulse response of an orthogonalized shock the average Treasury basis (in units of basis points) to the basis (Panel A) and the log spot exchange rate. The grey areas indicates 95% confidence intervals.

## 3 Convenience Yields and Asset Quantities

Finally, we consider the question of what drives the convenience yield. We present evidence from asset quantities that is analogous to Krishnamurthy and Vissing-Jorgensen (2012) who study the convenience yield on U.S. Treasury bonds. These authors posit that the convenience yield on

U.S. Treasury bonds is decreasing in the quantity of privately held Treasury bonds. The analog in our foreign case is that $\lambda^*$ is a decreasing function of the quantity of foreign held Treasury bonds. We obtain quarterly data from the Flow of Funds of the Federal Reserve on foreign holdings of U.S. Treasury bonds and construct the log of the ratio of these Treasury holdings to GDP (log $DY$) . The basis, $\overline{x}^{Treas}$ has a correlation coefficient of 0.23 with log $DY$. An OLS regression of the basis on log $DY$ gives a coefficient estimate of 9.8 with OLS $t-$statistic of 2.50. A higher D/Y ratio reduces the convenience yield, thereby making the US currency basis less negative. Note that log $DY$ is a slow moving variable and our sample only begins in 1988 compared to the roughly 100 year sample of Krishnamurthy and Vissing-Jorgensen (2012), so that the regression should be interpreted with some caution.

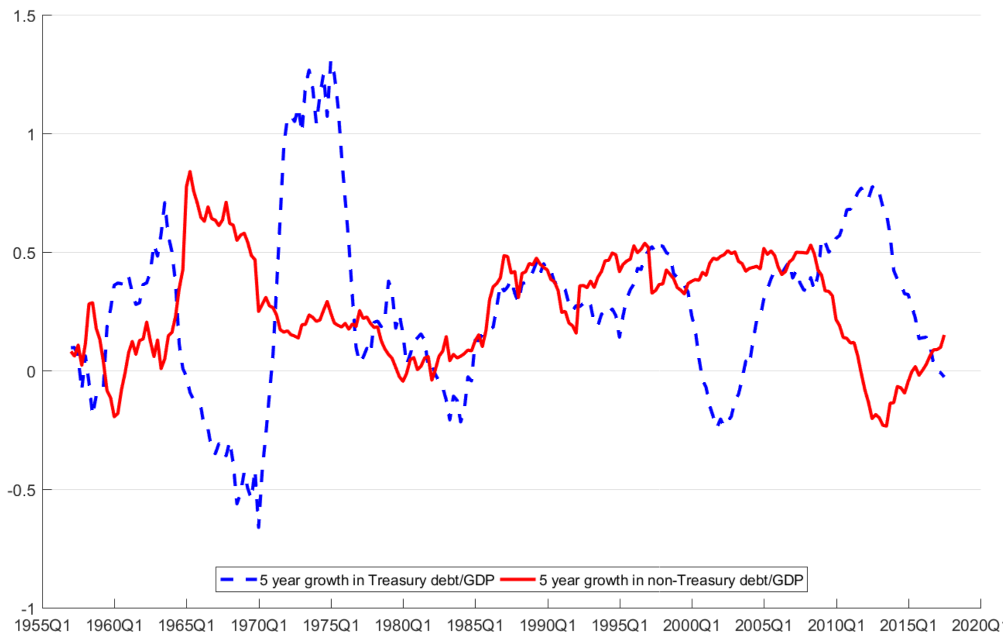


Figure 4: Growth in foreign holdings of Treasury and non-Treasury debt

Krishnamurthy and Vissing-Jorgensen (2012) derive a second prediction of the convenience yield hypothesis. They argue that as private Treasury holdings fall, holdings of assets which are substitutes for Treasury bonds, in particular bank deposits, will rise. We investigate this prediction of negative correlation in our context. We obtain data on foreign holdings of U.S. Treasury bonds back to 1951Q4 from the Flow of Funds. We also obtain data on U.S. assets which may be convenience substitutes.[8] We compute the ratio of this aggregate to GDP. We then correlate 5 year growth rates in this non-Treasury debt series with the 5 year growth rates of the $DY$ variable. The sample is from 1951Q4 to 2017Q2. Figure 4 graphs the series, which are evidently negatively correlated ($-0.31$). An OLS regression of the growth of $DY$ on growth of non-Treasury debt holdings to GDP gives a coefficient of $-0.52$ ($t-$statistic of 4.96).

Both of these pieces of evidence indicate that the basis reflects a convenience yield that foreign investors assign to U.S. safe assets. Given our empirical work documenting how the basis is related to the spot exchange rate, we conclude that the demand for safe assets is an important driver of the U.S. dollar exchange rate.

## 4 Conclusion

Du, Tepper, and Verdelhan (2017) have convincingly argued that Libor-based CIP deviations reflect the effects of frictions recently introduced in the financial intermediation sector, while Ivashina, Scharfstein, and Stein (2015) single out European banks who rely on dollar funding and were forced to borrow synthetic dollars during the eurozone crisis. Our work complements theirs by showing that safe asset demand for U.S. Treasurys can independently drive a wedge between currency-hedged Treasury yields and foreign yields. These wedges have explanatory power for variation in the dollar exchange rate, consistent with the convenience yield theory, even prior to the recent financial crisis. In contrast, the Libor basis covaries with the dollar exchange rate only after the financial crisis (see Avdjiev, Du, Koch, and Shin, 2016).

[8] These include flow of funds items repos, checkable deposits and currency, time and savings deposits, money market mutual fund shares, corporate and foreign bonds, commercial paper, and agency and GSE-backed securities.

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# A Siegel's paradox

We use $\lambda_t^{i,j}$ to denote investor's $i$ convenience yield for $j$'s bonds. Consider the foreign investor's equation for the foreign bond:

$$E_t[e^{-\rho_t^*} e^{y_t^*}] = e^{-\lambda_t^{*,*}}, \tag{14}$$

where $\lambda_t^{*,*}$ denotes the convenience yield foreigners impute to foreign bonds. Hence, the foreign bond yield is given by the foreign discount rate minus the convenience yield: $y_t^* = \rho_t^* - \lambda_t^{*,*}$. We allow for the possibility that U.S. investors receive convenience yields $\lambda_t^{\$,*}$ when holding foreign bonds,

$$E_t\left[e^{-\rho_t^{\$}} \frac{S_t}{S_{t+1}} e^{y_t^*}\right] = e^{-\lambda_t^{\$,*}}, . \tag{15}$$

This equation implies that the spot rates satisfy:

$$0 = \lambda_t^{\$,*} + y_t^* - \rho_t^{\$} - E_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}] \tag{16}$$

From the foreign investor's Euler equation for U.S. Treasurys, we had derived the following equation for the spot rates:

$$0 = \lambda_t^{*,\$} + (y_t^{\$} - y_t^*) - \lambda_t^{*,*} + E_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}] \tag{17}$$

By adding equation (16) to (17), we obtain the following result:

$$\lambda_t^{\$,*} + \lambda_t^{*,\$} + y_t^{\$} - \rho_t^{\$} + var_t[\Delta s_{t+1}] = 0$$

We also know that $y_t^{\$} = \rho_t^{\$} - \lambda_t^{\$,\$}$. Substitution of this equation implies the following equation restricts the convenience yields:

$$\lambda_t^{\$,*} + \lambda_t^{*,\$} - \lambda_t^{\$,\$} - \lambda_t^{*,*} = -var_t[\Delta s_{t+1}]$$

These convenience yields cannot all be zero, unless the variance of the exchange rate is zero.

Why is that? This is called Siegel's paradox (see Black, 1990). U.I.P. cannot hold for the U.S. and the foreign investor at the same time. In currency markets, it cannot be that both sides earn zero excess returns in levels. To see why, note that U.I.P. implies that the spot rates satisfy:

$$\begin{aligned} 0 &= (y_t^* - y_t^{\$}) - E_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}], \\ 0 &= (y_t^{\$} - y_t^*) + E_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}] \end{aligned}$$

That's a contradiction unless the variance is zero.

Next, to develop some intuition, consider the case in which only ownership of Treasurys deliver convenience yields. Then we have

$$\lambda_t^{*,\$} - \lambda_t^{\$,\$} = -var_t[\Delta s_{t+1}]$$

As $var_t[\Delta s_{t+1}] \to \infty$, then $\lambda_t^{*,\$} \to \lambda_t^{\$,\$}$. When there is no risk, the convenience yields have to be the same and the exchange rate is not affected by the convenience yield. To see why note that eqn. 17 reduces to:

$$0 = (\rho_t^{\$} - \rho_t^*) + E_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}], \tag{18}$$

which implies that convenience yields are irrelevant for exchange rates. Hence, in the risk-neutral case, an increase in foreign demand for Treasurys can only affect exchange rates if the variance of exchange rates decreases.

**Risk premia** Consider the case with risk premia. Let $RP_t^{*,\$}$ denote the currency risk premium in levels not logs. From the foreign investor's Euler equation for U.S. Treasurys, we had derived the following equation for the spot rates:

$$\begin{aligned} RP_t^{*,\$} - \lambda_t^{*,\$} + \lambda_t^{*,*} + &= (y_t^{\$} - y_t^*) + E_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}] \\ RP_t^{\$,*} + \lambda_t^{\$,\$} - \lambda_t^{\$,*} + &= (y_t^* - y_t^{\$}) - E_t[\Delta s_{t+1}] + \frac{1}{2} var_t[\Delta s_{t+1}]. \end{aligned}$$

Then we have the following restriction on the convenience yields:

$$\lambda_t^{\$,*} + \lambda_t^{*,\$} - \lambda_t^{\$,\$} - \lambda_t^{*,*} = RP_t^{\$,*} - RP_t^{*,\$} - var_t[\Delta s_{t+1}].$$

Next, to develop some intuition, consider the case in which only ownership of Treasurys deliver convenience yields. Then we have

$$\lambda_t^{*,\$} - \lambda_t^{\$,\$} = RP_t^{\$,*} - RP_t^{*,\$} - var_t[\Delta s_{t+1}].$$

An increase in $\lambda_t^{*,\$}$ would then have to be accompanied by a proportional increase in the risk premium U.S. investors ($RP_t^{\$,*}$) demand on foreign bonds.

# B A Theory of Spot Exchange Rates, Forward Exchange Rates and Convenience Yields on Bonds

We propose theory and provide supporting evidence to link the convenience yield on government debt to exchange rates. Our theory works as follows. There is a growing body of evidence that some government debt, and particularly U.S. government debt, offers liquidity and safety benefits to investors that leads to a low return on this debt (see Krishnamurthy and Vissing-Jorgensen, 2014, Greenwood, Hanson and Stein, 2015). Or alternatively, there is a convenience yield on U.S. government debt that reduces the monetary return to holding U.S. debt. Now suppose that the demand for these convenience services differs between U.S. and foreign investors. In particular suppose that the foreign investors derive greater convenience services from U.S. debt than do U.S. investors. Then, in equilibrium, foreign investors should receive a lower return *in their own currencies* on holding U.S. debt than U.S. investors. For this to happen, the U.S./Foreign exchange rate has to appreciate today, providing an expected depreciation, and thus delivering a lower return on the U.S. convenience asset to foreign investors than U.S. investors. Our theory predicts that when foreign investors increase their valuation of convenience properties of a given country's debt, the country's exchange rate will appreciate.

## B.1 Convenience yields and exchange rates

Denote $R_{t,k}^*[1_k]$ as the $k$-period return on a $k$-period risk-free zero-coupon bond in foreign currency. Likewise, denote $R_{t,k}[1_k]$ as the $k$-period return on a $k$-period risk-free zero-coupon bond in the home currency. The stochastic discount factor of the foreign investor is denoted $M_{t,k}^*$, while that of the home investor is denoted $M_{t,k}$.

The domestic pricing kernel must price the returns of home and foreign asset in their respective currencies. We depart from standard asset pricing by introducing a convenience yield term. In particular we write,

$$\begin{aligned} E_t\left(M_{t,k}R_{t,k}[1_k]\right) &= 1 - k \times \lambda_{t,k}^{home} \\ E_t\left(M_{t,k}\frac{S_{t+k}}{S_t}R_{t,k}^*[1_k]\right) &= 1 - k \times \lambda_{t,k}^{home,*}. \end{aligned}$$

for a home investor, where $S_{t+k}$ denotes the foreign exchange rate in units of home-per-foreign currency at time $t+k$. The terms $\lambda_{t,k}^{home}$ and $\lambda_{t,k}^{home,*}$ are the per-period convenience yield for a home investor investing in the bonds of the home and foreign countries.

In these Euler equations, we assume that investors are unconstrained in taking long or short positions in foreign or home bonds, or alternatively, that in equilibrium investors are holding strictly positive quantities of bonds. If there are short-sale constraints, as is realistic for many convenience assets, then we would alter these expressions to reflect the Lagrange multiplier on the short-sale constraint.

For the foreign investor, we also have a pair of Euler equations for investing in the home and foreign bond:

$$\begin{aligned} E_t\left(M^*_{t,k}R^*_{t,k}[1_k]\right) &= 1-k\times\lambda^{foreign,*}_{t,k} \\ E_t\left(M^*_{t,k}\frac{S_t}{S_{t+k}}R_{t,t+k}[1_k]\right) &= 1-k\times\lambda^{foreign}_{t,k}. \end{aligned}$$

We follow the approach of Backus, Foresi, and Telmer (2001) by considering the following pair of Euler equations to determine a candidate exchange rate process:

$$E_t\left(M^*_{t,k}R^*_{t,k}[1_k]\right) = 1-k\times\lambda^{foreign,*}_{t,k} \quad \text{and} \quad E_t\left(M_{t,k}\frac{S_{t+k}}{S_t}R^*_{t,k}[1_k]\right) = 1-k\times\lambda^{home,*}_{t,k}.$$

To satisfy these Euler equations, we conjecture an exchange rate process that satisfies,

$$\frac{M^*_{t,k}}{1-k\times\lambda^{foreign,*}_{t,k}} = \frac{M_{t,k}}{1-k\times\lambda^{home,*}_{t,k}}\frac{S_{t+k}}{S_t}.$$

This guess, as can easily be verified, satisfies the Euler equations. If financial markets are complete, then this is the unique exchange rate process that is consistent with the absence of arbitrage opportunities. Using lower case letters to denote logs, and log-linearizing this expression, we find:

$$\Delta s_{t,k} = \left(m^*_{t,k}-m_{t,k}\right)+k\times\left(\lambda^{foreign,*}_{t,k}-\lambda^{home,*}_{t,k}\right) \tag{19}$$

The difference in convenience valuation of the foreign bond, across foreign and home investors, determines movements in the exchange rate. All else equal, an increase in the convenience yield on the foreign risk-free bond coincides with an instantaneous appreciation of the foreign currency.

To give an example, suppose that home is Canada and foreign is the U.S.. The home (Canada) investor increases his convenience valuation of U.S. bonds, causing $\lambda^{home,*}_{t,k}$ to rise. As a result, $\Delta s_{t,k}$ falls. The exchange rate in units of CAD-per-USD is expected to fall; or, the CAD is expected to appreciate. We can understand this dynamic as a shock to convenience demand causes the USD to appreciate, and then give an expected depreciation.

We rewrite (19) further. In particular, we can use the Euler equations for the home investor in the home bond and foreign investor in the foreign bond to derive,

$$E_t\left(m_{t,k}\right)+k\times y_{t,k}+L_t\left(m_{t,k}\right) = -k\times\lambda^{home}_{t,k} \tag{20}$$

$$E_t\left(m^*_{t,k}\right)+k\times y^*_{t,k}+L_t\left(m^*_{t,k}\right) = -k\times\lambda^{foreign,*}_{t,k}, \tag{21}$$

where $L_t\left(m_{t,k}\right)$ is the conditional entropy of the stochastic discount factor. That is, $L_t\left(m_{t,k}\right) = \log E_t\left(m_{t,k}\right) - E_t \log\left(m_{t,k}\right)$. Here, $y_{t,k}$ is the annualized yield on the $k$ period bond.

We then take expectations of both sides of (19) and use (20) and (21) to find,

$$E_t[\Delta s_{t,k}] + k \times (y^*_{t,k} - y_{t,k}) = L_t\left(m_{t,k}\right) - L_t\left(m^*_{t,k}\right) + k \times \left(\lambda^{home}_{t,k} - \lambda^{home,*}_{t,k}\right) \tag{22}$$

The left hand side is the excess return on investing in the foreign bond relative to the home bond. This is the familiar carry trade return. On the right hand side, the first pair of terms are the familiar sources of carry trade return, namely the conditional risk attached to these trades. The second pair of terms are the new terms from our theory, which are the convenience yield terms. Hence, even in the absence of priced currency risk $L_t\left(m_{t,k}\right) - L_t\left(m^*_{t,k}\right) = 0$, U.I.P. fails.

Finally, we note that these Euler equations can also be combined using positions in the home bond. That is, consider the following pair of Euler equations:

$$E_t\left(M_{t,t+k} R_{t,k}[1_k]\right) = 1 - k \times \lambda^{home}_{t,k} \quad \text{and} \quad E_t\left(M^*_{t,k} \frac{S_t}{S_{t+k}} R_{t,t+k}[1_k]\right) = 1 - k \times \lambda^{foreign}_{t,k}.$$

To satisfy these Euler equations, we conjecture an exchange rate process that satisfies,

$$\Delta s_{t,k} \quad = \quad \left(m^*_{t,k} - m_{t,k}\right) + k \times \left(\lambda^{foreign}_{t,k} - \lambda^{home}_{t,k}\right)$$

which can be rewritten as,

$$E_t[\Delta s_{t,k}] + k \times (y^*_{t,k} - y_{t,k}) = L_t\left(m_{t,k}\right) - L_t\left(m^*_{t,k}\right) + k \times \left(\lambda^{foreign}_{t,k} - \lambda^{foreign,*}_{t,k}\right)$$

Thus our model imposes a link between the equilibrium relative convenience for home and foreign bonds. When the Canadian investor increases $\lambda^{home,*}_{t,k}$, either he must also be increasing $\lambda^{home}_{t,k}$ (the Canadian investor's convenience yield for the Canadian bond) or the U.S. investor must be decreasing $\lambda^{foreign}_{t,k}$ (the U.S. investor's convenience yield for the Canadian bond).[9]

## B.2 Convenience yields and CIP

We next posit that Covered Interest Rate Parity (CIP) does not hold in our setting. Suppose the home investor can invest in the foreign bond, but via hedging the currency risk in the forward market:

$$E_t\left(M_{t,k} \frac{F^k_t}{S_t} R^*_{t,k}[1_k]\right) = 1 - k \times \lambda^{home,*hedged}_{t,k}.$$

[9] Another possibility is that $\lambda^{foreign}_{t,k}$ falls to zero, and U.S. holdings of the Canadian bond fall to zero, but given short-sale constraints, they do not fall below zero. In this latter case, the Euler equation governing U.S. investments in the Canadian should be read as an inequality restriction. But note that the Euler equation governing Canadian investments in the U.S. bond can still hold with equality.

The hedged investment also offers a convenience yield. For example, the Canadian investor receives a convenience yield when holding the U.S. bond on a hedged basis, leading to $\lambda_{t,k}^{home,*hedged} > 0$.

We can combine this expression with $E_t\left(M_{t,k}R_{t,k}[1_k]\right) = 1 - k \times \lambda_{t,k}^{home}$ to find:

$$\frac{F_t^k}{S_t} = \frac{1 - k \times \lambda_{t,k}^{home,*hedged}}{1 - k \times \lambda_{t,k}^{home}} \frac{R_{t,k}[1_k]}{R_{t,t+1}^*[1_k]}$$

Then, taking logs, we have that:

$$\frac{1}{k}(f_{t,k} - s_t) = (\lambda_{t,k}^{home} - \lambda_{t,k}^{home,*hedged}) + (y_{t,k} - y_{t,k}^*)$$

Hence the foreign currency basis is given by:

$$\frac{1}{k}(f_{t,k} - s_t) - (y_{t,k} - y_{t,k}^*) = \lambda_{t,k}^{home} - \lambda_{t,k}^{home,*hedged}.$$

Or defining the basis:

$$x_{t,k} \equiv y_{t,k}^* - (y_{t,k} - \frac{1}{k}(f_{t,k} - s_t)) = \lambda_{t,k}^{home} - \lambda_{t,k}^{home,*hedged}. \tag{23}$$

The basis captures the home investor's relative convenience valuations for investing in the home bond versus the foreign-hedged bond.

In a model with no convenience yields, the foreign currency basis is zero. The existence of a convenience yield drives the basis away from zero. In the Canada/U.S. case we have given, we would expect that $\lambda_{t,k}^{home,*hedged} > \lambda_{t,k}^{home}$ so that $x_{t,k}$ is negative.

Note that a negative basis for one investor (Canada) means a positive basis for the other (U.S.). In particular, consider $\lambda_{t,k}^{foreign,hedged}$. This is the value to a U.S. investor of investing, on a hedged basis, in the Canadian government bond. It is easy to verify that,

$$\frac{F_t^k}{S_t} = \frac{1 - k \times \lambda_{t,k}^{foreign*}}{1 - k \times \lambda_{t,k}^{foreign,hedged}} \frac{R_{t,k}[1_k]}{R_{t,t+1}^*[1_k]}$$

and hence,

$$\frac{1}{k}(f_{t,k} - s_t) - (y_{t,k} - y_{t,k}^*) = \lambda_{t,k}^{foreign,hedged} - \lambda_{t,k}^{foreign,*}.$$

If the basis is negative, it must mean the U.S. investors derive less convenience from investing in the hedged Canadian bond than in the U.S. Treasury bond. That is, they too prefer investing in U.S. bonds.

## B.3 Testing the model

Our key assumption is that $\lambda_{t,k}^{home,*hedged}$ is positively related to $\lambda_{t,k}^{home,*}$:

$$\lambda_{t,k}^{home,*} = \phi \lambda_{t,k}^{home,*hedged} + u_{t,k}, \quad , \phi > 0 \tag{24}$$

where $u_{t,k}$ is orthogonal to all other shocks. Canadian demand for U.S. bonds leads $\lambda_{t,k}^{home,*}$ (the convenience valuation of the U.S. government bond to rise) and $\lambda_{t,k}^{home,*hedged}$ to rise (the convenience valuation of an FX hedged U.S. government bond to rise). This assumption seems reasonable. Under this assumption, the currency basis should forecast exchange rates.

We substitute from (24) into (22) (and take expectations) to find,

$$E_t[\Delta s_{t,k}] + k \times (y_{t,k}^* - y_{t,k}) = L_t\left(m_{t,k}\right) - L_t\left(m_{t,k}^*\right) + k \times \left(\lambda_{t,k}^{home} - \phi \lambda_{t,k}^{home,*hedged}\right).$$

Next we use the expression for the basis to derive a relation between the basis and exchange rates. We substitute for $\lambda_{t,k}^{home,*hedged}$ from the expression for the basis, (23), to find our main theoretical result:

**Proposition 1.** *The expected log excess return on the long position in foreign Treasury bonds is increasing in the risk premium and the Treasury basis:*

$$E_t[\Delta s_{t,k}] + k \times (y_{t,k}^* - y_{t,k}) \quad = \quad L_t\left(m_{t,k}\right) - L_t\left(m_{t,k}^*\right) + k \times \left(\phi x_{t,k} + (1-\phi)\lambda_{t,k}^{home}\right) \tag{25}$$

In the case where $\phi = 1$, the expected log return on the foreign Treasury in excess of the log return on domestic Treasury bond equals the standard currency risk premium plus the basis. All else equal, a decline in the basis due to an increase in the convenience yield on foreign government bonds reduces the expected log excess return. Even in the absence of a foreign currency risk premium, i.e. $L_t(M_{t,k}) = L_t(M_{t,k}^*)$, uncovered interest rate parity (U.I.P.) may fail if the basis is different from zero. We can understand this result as, when Canadian demand for U.S. bonds rises, the basis goes negative, and the Dollar exchange rate jumps up, leading to an expected depreciation.[10]

**Proposition 2.** *The expected log return to going long the foreign currency via the forward contract is:*

$$E_t[\Delta s_{t,k}] - (f_{t,k} - s_t) \quad = \quad L_t\left(m_{t,k}\right) - L_t\left(m_{t,k}^*\right) + k(1-\phi) \times \lambda_{t,k}^{home,*hedged}. \tag{26}$$

[10]We can also construct this relation from the standpoint of the foreign investor. To see, this assume that $\lambda_{t,k}^{foreign,hedged} = \phi \lambda_{t,k}^{foreign}$. That is, U.S. investors' convenience valuation of the Canadian bond is positively related to their convenience valuation of investing in an FX-hedged bond. Then we can substitute to find that,

$$E_t[\Delta s_{t,k}] + k \times (y_{t,k}^* - y_{t,k}) = L_t\left(m_{t,k}\right) - L_t\left(m_{t,k}^*\right) + k \times (\phi x_{t,k} - (1-\phi)\lambda^{foreign,*}).$$

*The expected drift in the log exchange rate is:*

$$E_t[\Delta s_{t,k}] \quad = \quad E_t\left(m^*_{t,k}\right) - E_t\left(m_{t,k}\right) + k \times \left(\phi x_{t,k} + \lambda^{foreign,*}_{t,k} - \phi \lambda^{home}_{t,k}\right). \tag{27}$$

Let us focus on the maturity $k = 1$. By forward iteration on eqn. (25), this expression implies that the level of exchange rates can be stated as a function of the interest rate differences, the currency risk premia and the future bases (see Froot and Ramadorai, 2005, for a version without convenience yields).

**Proposition 3.** *The level of the exchange can be written as:*

$$s_t = E_t \sum_{j=0}^{\infty} (y^*_{t+j} - y_{t+j}) - E_t \sum_{j=0}^{\infty} rp^{FX}_{t+j} - E_t \sum_{j=0}^{\infty} \left(\phi x_{t+j} + (1-\phi)\lambda^{home}_{t+j}\right) + \bar{s}$$

*where* $rp^{FX}_t = L_t\left(m_{t,t+1}\right) - L_t\left(m^*_{t,t+1}\right)$. *The term* $\bar{s} = E_t[\lim_{j\to\infty}\ s_{t+j}]$ *which is constant under the assumption that the exchange rate is stationary.*

We can rearrange terms to also derive some other expressions that we use in our empirical work.

# C Data Appendix

For the FX source, before December 1996, we use the Barclays Bank source from Datastream. After December 1996, we use World Markets Reuters (WMR) from Datastream. The Datastream codes for the spot rates and 12M forward rates are: *BBGBPSP, BBGBPYF, BBAUDSP, BBAUDYF, BBCADSP, BBCADYF, BBDEMSP, BBDEMYF, BBJPYSP, BBJPYYF, BNZDSP, BBNZDYF, BBNOKSP, BBNOKYF, BBSEKSP, BBSEKYF, BBCHFSP, BBCHFYF, AUSTDOL, UKAUDYF, CNDOLLR, UKCADYF, DMARKER, UKDEMYF, JAPAYEN, UKJPYYF, NZDOLLR, UKNZDYF, NORKRON, UKNOKYF, SWEKRON, UKSEKYF, SWISSFR, UKCHFYF, UKDOLLR, UKUSDYF.*

For the Government Bond Yields (see Table 4), most country-maturities pairs only use one source, except if there are gaps. If there are gaps, we use all the data from the first source wherever available, as indicated in the Table, and then fill in any gaps for some year month using the second data source (indicated by '2').

For LIBORs (see Table 5), we use the BBA-ICE LIBOR when available. Coverage is good for Germany, Japan, Switzerland, UK, and U.S.. For other countries, we then use other interbank survey rates (BBSW, CDOR, NIBOR, STIBOR) to fill in any gaps. We then use deposit rates (Bank Bill, NKD, SKD) for any remaining gaps.

Table 3: Country Composition of Unbalanced Panel

| Country | Maturity | Source | Ranges | | | |
|---|---|---|---|---|---|---|
| 'Australia' | 12 | All | 199912 - 201707 | | | |
| 'Canada' | 12 | All | 199312 - 201707 | | | |
| 'Germany' | 12 | All | 199707 - 201707 | | | |
| 'Japan' | 12 | All | 199504 - 201707 | | | |
| 'New Zealand' | 12 | All | 199603 - 200905 | 201006 - 201212 | 201310 - 201412 | 201606 - 201707 |
| 'Norway' | 12 | All | 199001 - 199611 | 199701 - 201707 | | |
| 'Sweden' | 12 | All | 199103 - 199611 | 199701 - 201304 | 201306 - 201707 | |
| 'Switzerland' | 12 | All | 198801 - 201707 | | | |
| 'United Kingdom' | 12 | All | 199707 - 201707 | | | |
| 'United States' | 12 | All | 198801 - 201707 | | | |

Table 4: Sources for Government Bond Yields

| Country | Maturity | Months | | Mnemonic |
|---|---|---|---|---|
| 'Australia' | 12 | 'Bloomberg' | | GTAUD1Y Govt |
| 'Canada' | 12 | 'Bank of Canada (Datastream)' | | CNTBB1Y |
| 'Germany' | 12 | 'Bloomberg' | | GTDEM1Y Govt |
| 'Japan' | 12 | 'Bloomberg' | | GTJPY1Y Govt |
| 'New Zealand' | 12 | 'Bloomberg' | 1 | GTNZD1Y Govt |
| 'New Zealand' | 12 | 'Reserve Bank of New Zealand (Datastream)' | 2 | NZGBY1Y |
| 'Norway' | 12 | 'Oslo Bors' | | ST3X |
| 'Sweden' | 12 | 'Sveriges Riksbank (Cristina)' | 2 | |
| 'Sweden' | 12 | 'Sveriges Riksbank (website)' | 1 | |
| 'Switzerland' | 12 | 'Swiss National Bank' | | |
| 'United Kingdom' | 12 | 'Bloomberg' | | GTGBP1Y Govt |
| 'United States' | 12 | 'Bloomberg' | 1 | GB12 Govt |
| 'United States' | 12 | 'FRED' | 2 | |

The numbers indicate which source takes precedence.

Table 5: Sources for LIBOR

| Country | Maturity | Source | Mnemonic |
|---|---|---|---|
| 'Australia' | 12 | 'Bank Bill (Bloomberg)' | ADBB12M Curncy |
| 'Australia' | 12 | 'Bank Bill Swap (Bloomberg)' | BBSW1Y Index/BBSW1MD Index |
| 'Canada' | 12 | 'CDOR (Bloomberg)' | CDOR12 Index |
| 'Australia' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBAUD12 |
| 'New Zealand' | 12 | 'Bank Bill (Bloomberg)' | NDBB12M Curncy |
| 'Canada' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBCAD12 |
| 'Germany' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBDEM12 |
| 'Japan' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBJPY12 |
| 'New Zealand' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBNZD12 |
| 'Norway' | 12 | 'NIBOR (Bloomberg)' | NIBOR12M Index |
| 'Norway' | 12 | 'Norwegian Krone Deposit (Bloomberg)' | NKDR1 Curncy |
| 'Sweden' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBSEK12 |
| 'Sweden' | 12 | 'STIBOR (Bloomberg)' | STIB1Y Index |
| 'Sweden' | 12 | 'Swedish Krona Deposit (Bloomberg)' | SKDR1 Curncy |
| 'Switzerland' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBCHF12 |
| 'United Kingdom' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBGBP12 |
| 'United States' | 12 | 'BBA-ICE LIBOR (Datastream)' | BBUSD12 |