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ABSTRACT

We develop a theory that links foreign investors' demand for the safety of U.S. Treasury bonds to the value of the dollar in spot markets. An increase in the convenience yield that foreign investors derive from holding U.S. Treasurys induces an immediate appreciation of the US dollar and, going forward, lowers the expected return to a foreign investor from owning Treasury bonds. Under our theory, we show that the foreign convenience yield can be measured by the 'Treasury basis,' defined as the wedge between the yield on foreign government bonds and the currency-hedged yield on U.S. Treasury bonds. We measure the convenience yield using data from a cross-country panel going back to 1988 and the US/UK cross going back to 1970. In both datasets, regression evidence strongly supports the theory. Our results help to resolve the exchange rate disconnect puzzle: the Treasury basis variation accounts for up to 41% of the quarterly variation in the dollar. Our results also provide support for recent theories which ascribe a special role to the U.S. as a provider of world safe assets.

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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 offered by U.S. Treasury bonds (see Krishnamurthy and Vissing-Jorgensen, 2012, for example). Figure 1 illustrates this pattern during 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 during 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 cumulative value of all future convenience yields.

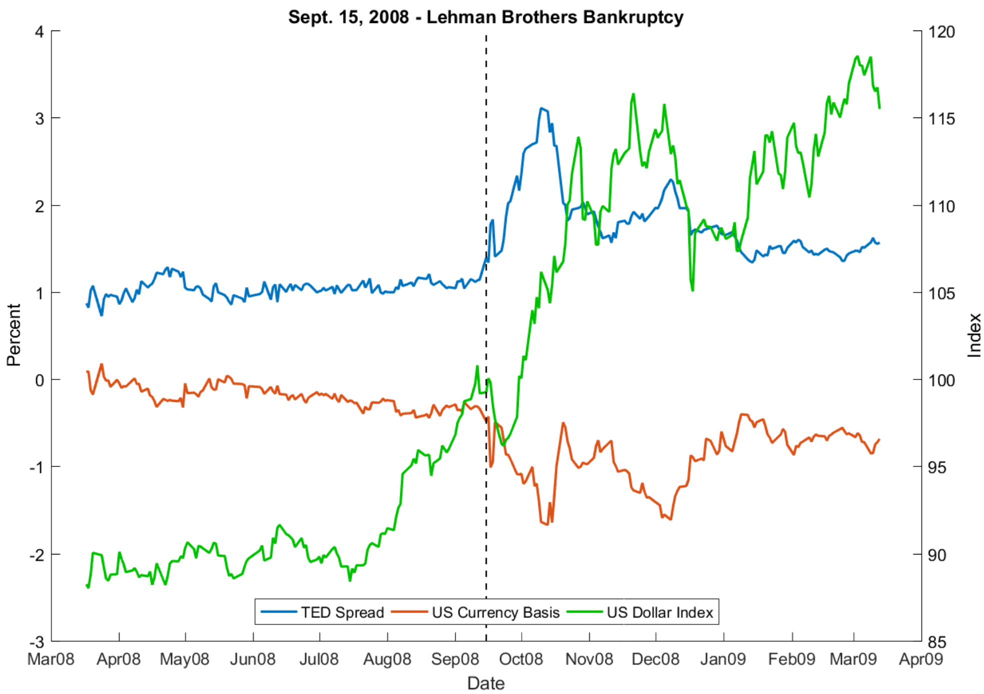

Figure 1: TED Spread, Average Treasury Basis and Dollar.

Our theory rests on the premise that the U.S. Treasury is the world's most favored supplier of safe assets, and that foreign investors pay a sizeable premium to own these assets. There is a growing body of literature that analyzes the key role of the U.S. as the world's safe asset supplier (see Gourinchas and Rey, 2007; Caballero, Farhi and Gourinchas, 2008; Caballero and Krishnamurthy, 2009; Maggiori, 2017; He, Krishnamurthy and Milbradt, 2017; Gopinath and Stein, 2017).[1] Our paper develops a theory of the dollar exchange rate that imputes a central role to the convenience yields that foreign investors derive from the ownership of U.S. Treasurys. We then provide systematic evidence, beyond Figure 1, in support of the theory.

U.S. Treasury bonds are known to offer liquidity and safety services to investors which results in lower equilibrium returns to investors from holding such bonds (see Krishnamurthy and Vissing-Jorgensen, 2012; Greenwood, Hanson and Stein, 2015). Our paper explores the implications of foreign investors imputing a higher convenience yield to U.S. Treasurys than U.S. investors. This being the case, in equilibrium, foreign investors should receive a lower return *in their own currencies* on holding U.S. Treasurys than U.S. investors. To produce lower expected returns on U.S. Treasurys in foreign currency, the dollar has to appreciate today and, going forward, depreciate in expectation to deliver a lower expected return to foreign investors than U.S. investors. We derive a novel expression for the dollar exchange rate as the expected value of all future interest rate differences and convenience yields less the value of all future currency risk premia, extending the work by Froot and Ramadorai (2005) and Engel and West (2005). Our theory predicts that a country's exchange rate will appreciate whenever foreign investors increase their valuation of the current and future convenience properties of that country's debt.

To test the theory, we need a measure of the foreign convenience yield on U.S. Treasury bonds. We posit that foreigners also derive convenience value from a hedged position in U.S. Treasurys. In this case a wedge appears between the yield on foreign government bonds and the currency-hedged yield on U.S. Treasury bonds. Our key assumption is that this wedge, which we refer to as the dollar Treasury basis, is proportional to the convenience yield foreign investors derive from an unhedged position in Treasurys. We can measure the dollar Treasury basis using data on spot exchange rates, forward exchange rates, and pairs of government bond yields. We use two datasets, a cross-country panel beginning in 1988 and going to 2017 and a US/UK time series that starts in 1970 and ends in 2017. The theory finds strong support in both datasets. The wedge is generally

[1] There is related but distinct literature on the special role of the US dollar and US asset markets in the world economy. See Gourinchas, Rey and Govillot (2011) on the "exorbitant privilege" of the US that drives low rates of return on US dollar assets. In their analysis, the low return stems the role of the US in international risk sharing. See Lustig, Roussanov and Verdelhan (2014) on evidence for a global dollar factor driving currency returns around the world. See Gopinath (2015) for evidence on the dominant role of the dollar as an invoicing currency.

negative and more negative during global financial crises, consistent with the picture from Figure 1. Innovations in the dollar basis account for between 13% to 41% of the variation in the spot dollar exchange rate with the right sign: a decrease in the dollar basis coincides with an appreciation of the dollar. These numbers are high in light of the well-known exchange rate disconnect puzzle (Froot and Rogoff, 1995; Frankel and Rose, 1995). Using a Vector Autoregression to model the joint dynamics of the dollar basis, the interest rate difference and the exchange rate, we find that a 10 basis point rise in the basis drives a 1.5% depreciation in the dollar over the next quarter. Subsequently, there is a gradual reversal over the next two to three years as the high basis leads to a positive excess return on owning the US dollar.

Using our new convenience-yield valuation equation for the exchange rate, we implement a Campbell-Shiller style decomposition of exchange rate innovations into a cash flow component which tracks interest rate differences, a discount rate component which tracks currency risk premia, and, finally, a convenience yield component. In Froot and Ramadorai (2005)'s decomposition, the latter would have been absorbed by the discount rate component. The convenience yield channel is quantitatively important: it accounts for about 60% of the real US/UK exchange rate variance; the discount rate component accounts for roughly 120%, and the two components are strongly positively correlated.

Contribution to the literature on exchange rate disconnect: Researchers have struggled to identify the fundamental drivers of the exchange rate (the 'exchange rate disconnect puzzle', see Froot and Rogoff (1995); Frankel and Rose (1995)). We help resolve this puzzle by linking variation in safe asset demand to quarterly variation in exchange rates, and finding regression R^2s as high as 41%.[2] Convenience yields enter as wedge into the foreign investors' Euler equation and the uncovered interest parity condition. Adopting a preference-free approach, Lustig and Verdelhan (2016) demonstrate that a large class of incomplete markets models without these wedges cannot simultaneously address the U.I.P. violations, the exchange rate disconnect and the exchange rate volatility puzzles, while Itskhoki and Mukhin (2017) argue that models with such a wedge are one way to solve the exchange rate disconnect puzzle. Real exchange rates do not co-vary with macroeconomic quantities in the right way (see Backus and Smith, 1993; Kollmann, 1995). The existence of convenience yields introduces a wedge between the real exchange rates and the difference in the log pricing kernels that may help to resolve this issue.

[2]In high frequency data, there is evidence for order flows driving exchange rate dynamics. (see Jeanne and Rose, 2002; Evans and Lyons, 2002; Hau and Rey, 2005, for recent examples).

A large class of theoretical models predict that interest rates should drive exchange rates. Some papers have confirmed this finding, but the results are mixed and do not always conform to theory. For example, Eichenbaum and Evans (1995) find that an increase in home rates appreciates the home currency, as would be suggested by textbook models. Textbook models predict that the exchange rate should be expected to depreciate after an unexpected increase in the home interest rate, but U.I.P. is soundly rejected in the data, as is well known since the seminal work of Hansen and Hodrick (1980); Fama (1984): the currency of the high interest rate currency subsequently appreciates on average. Recently, Engel (2016); Valchev (2016); Dahlquist and Penasse (2016) show that an increase in the short-term interest rate initially causes the dollar to appreciate, but subsequently the dollar depreciates.[3] We find that the initial appreciation in response to an interest rate shock disappears when basis shocks are introduced.

Contribution to the safe assets literature: Our results lend empirical support to theories of the U.S. as the provider of world safe assets. There is ample empirical evidence that non-US borrowers tilt the denomination of their borrowings (loans, deposits, bonds) especially towards the US dollar: Shin (2012) and Ivashina, Scharfstein and Stein (2015) on bank borrowing, Bräuning and Ivashina (2017) on loan denomination, and Bruno and Shin (2017) on corporate bond borrowing. Moreover, foreign investors tilt their portfolio towards owning US dollar-denominated corporate bonds when they invest in bonds denominated in foreign currencies (see Maggiori, Neiman and Schreger, 2017). The evidence on the dollar bias in credit markets is silent on whether demand or supply factors are the main drivers.[4] Our evidence from sovereign bond markets supports a demand-based explanation. The Treasury dollar basis is typically negative and reductions in the basis appreciate the dollar, suggesting that foreign investor's special demand for dollar-denominated assets lowers their expected returns.

Our theory posits a special role for the dollar simply because Treasurys are denominated in dollars. There is empirical evidence to support the notion that the dollar is different from other currencies. The dollar carry trade which goes long in a basket of foreign currencies when the foreign-minus-US interest rate gap is positive is highly profitable (Lustig, Roussanov and Verdelhan, 2014). This is not the case for other currencies (Hassan and Mano, 2014). Our theory predicts that, all else equal, a widening of the dollar basis, is accompanied by an increase in the risk premium that U.S. investors demand on a long position in foreign currency. However, the dollar continues to appreciate for another quarter after the widening of the basis. Since the dollar basis

[3] Engel (2016) shows that these dynamics cannot be matched by standard asset pricing models.

[4] The quantity evidence does not identify whether the bias towards dollar assets is demand or supply-driven.

typically widens when the interest rate gap increases, this could help explain the profitability of the dollar carry trade.

Relation to the literature: The evidence we present is most closely related to Valchev (2016) who shows that the quantity of U.S. Treasury bonds outstanding helps to explain the return on the dollar. Valchev (2016) builds an open-economy model to relate the quantity of US Treasury bonds to the convenience yield on Treasury bonds and the failure of uncovered interest parity. We show that the existence of a foreign convenience yield for US Treasury bonds causes both uncovered interest parity and covered interest parity to fail. Moreover, we show that variation in the convenience yields as measured by the dollar basis explains a sizeable portion of the variation in the dollar exchange rate.

There is a recent literature examining the failure of covered interest rate parity (C.I.P.). Our Treasury basis measure is closely related to the C.I.P. deviation. That deviation is constructed using LIBOR rates for home and foreign countries while our basis measure is the same deviation but constructed using government bond yields for home and foreign countries. In an influential recent paper, Du, Tepper and Verdelhan (2017) document that the LIBOR basis was near zero pre-crisis and has often been significantly different than zero post-crisis. They show that the movements in the LIBOR basis are closely connected to frictions in financial intermediation that prevent arbitrage activities. Other papers have come to similar conclusions regarding the importance of financial frictions and capital controls. See Ivashina, Scharfstein and Stein (2015), Gabaix and Maggiori (2015), Amador et al. (2017), and Itskhoki and Mukhin (2017). Our paper simply points out that covered interest rate parity cannot hold for Treasurys when their ownership produces convenience yields, while foreign bonds do not, even in the absence of frictions. Moreover, we explain how financial frictions considerations can be introduced into our theory. We show that without such frictions, the LIBOR basis, but not the Treasury basis, will be zero. With such frictions, the LIBOR basis will differ from zero, increase the Treasury basis, and drive a relation between the LIBOR basis and the dollar exchange rate. We show that these predictions hold-up in the data.

The paper proceeds as follows. The next section lay out the convenience yield theory. Section 2 take the theory to data. Section 3 further discusses the empirical and theoretical results. The appendix provides further derivations of the theory, additional empirical evidence, and details our data sources.

1 A Theory of Spot Exchange Rates, Forward Exchange Rates and Convenience Yields on 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 and exchange rate pricing conditions that must be satisfied in asset market equilibrium. For ease of exposition, we assume that only U.S. Treasurys produce convenience yields. We relax this assumption in Section 1.7.

1.1 Convenience yields and exchange rates

Denote y_t^* as the yield on a one-period risk-free zero-coupon bond in foreign currency. Likewise, denote $y_t^\$$ as the yield on a one-period risk-free zero-coupon bond in dollars. The stochastic discount factor (SDF) of the foreign investor is denoted M_t^*, while that of the US investor is denoted $M_t^\$$.

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

$$E_t\left(M_{t+1}^* e^{y_t^*}\right) = 1 \tag{1}$$

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,

$$E_t\left(M_{t+1}^* \frac{S_{t+1}}{S_t} e^{y_t^\$}\right) = e^{-\lambda_t^*}, \quad \lambda_t^* \geq 0. \tag{2}$$

The expression on the left side of the equation is standard. On the right side, we allow foreign investors in U.S. Treasurys to derive a convenience yield, λ_t^*, on their Treasury bond holdings. This λ_t^* is asset-specific. 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 appreciation declines or the yield $y_t^\$$ declines, or both.

Next, we use these pricing conditions to derive an expression linking the exchange rate and the convenience yield. We assume that $m_t^* = \log\ M_t^*$ and $\Delta s_{t+1} = \log \frac{S_{t+1}}{S_t}$ are conditionally normal. Then, (1) can be rewritten as,

$$E_t\left(m_{t+1}^*\right) + \frac{1}{2}Var_t\left(m_{t+1}^*\right) + y_t^* = 0, \tag{3}$$

and (2) as,

$$E_t\left(m_{t+1}^*\right) + \frac{1}{2}Var_t\left(m_{t+1}^*\right) + E_t[\Delta s_{t+1}] + \frac{1}{2}var_t[\Delta s_{t+1}] + y_t^{\$} + \lambda_t^* - RP_t^* = 0. \tag{4}$$

Here $RP_t^* = -cov_t\left(m_{t+1}^*, \Delta s_{t+1}\right)$ is the risk premium the foreign investor requires for the exchange rate risk when investing in US bonds. We combine these two expressions to find that the expected return in levels on a long position in dollars earned by a foreign investor is given by:

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

The left hand side is the excess return to a foreign investor from investing in the US bond relative to the foreign bond. This is the return on the reverse carry trade, given that US yields are typically lower than foreign yields. On the right hand side, the first term is the familiar currency risk premium demanded by a foreign investor going long US Treasurys in dollars. The second term is the convenience yield attached by foreign investors to U.S. Treasurys: A positive convenience yield lowers the return on the reverse carry trade, i.e., the return to investing in US Treasury bonds. Even in the absence of priced currency risk, $RP_t^* = 0$, U.I.P. fails when the convenience yield is greater than zero, as previously pointed out by Valchev (2016).

Finally, this analysis does not hinge on the log-normality assumption. We use $L_t(X_{t+1}) = \log E_t(X_t) - E_t \log(X_{t+1})$ to denote the conditional entropy of X_t. If we do not assume log-normality, we can derive the following expression for the expected excess return:

$$E_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^*\right) + L_t\left(\frac{S_{t+1}}{S_t}\right) = RP_t^* - \lambda_t^* \tag{6}$$

where $RP_t^* = -\left(L_t\left(M_{t+1}^* \frac{S_{t+1}}{S_t}\right) - L_t\left(M_{t+1}^*\right) - L_t\left(\frac{S_{t+1}}{S_t}\right)\right)$. Backus, Chernov and Zin (2014) refer to $L_t(X_{t+1}Y_{t+1}) - L_t(X_{t+1}) - L_t(Y_{t+1})$ as the co-entropy of X and Y. All our derivations can be rewritten in terms of conditional entropy rather than the conditional variance of the exchange rate. Nevertheless, we develop expressions based on log-normality, and the conditional variance term, primarily for simplicity.

1.2 U.S. demand for foreign bonds

Since U.S. investors have access to foreign bond markets, there is another pair of Euler equations to consider. An increase in the foreign convenience yield imputed to U.S. Treasurys implies an expected deprecation of the dollar. For a U.S. investor, buying foreign bonds when the dollar is expected to depreciate produces a high carry return. The U.S. investor's Euler equation when investing in the foreign bond is:

$$E_t\left(M_{t+1}^{\$}\frac{S_t}{S_{t+1}}e^{y_t^*}\right)=1. \tag{7}$$

We also assume that U.S. investors derive a convenience yield when investing in U.S. Treasurys:

$$E_t\left(M_{t+1}^{\$}e^{y_t^{\$}}\right)=e^{-\lambda_t^{\$}}. \quad \lambda_t^{\$}\geq 0. \tag{8}$$

$\lambda_t^{\$}$ is asset-specific. An increase in the U.S. investor's convenience yield lowers U.S. Treasury bond yields, holding the SDF fixed: $y_t^{\$}=\rho_t^{\$}-\lambda_t^{\$}$, where $\rho_t^{\$}=-\log E_t\left(M_{t+1}^{\$}\right)$.
We assume log-normality and rewrite these equations to derive an expression for the carry trade return,

$$\left(y_t^*-y_t^{\$}\right)-E_t[\Delta s_{t+1}]+\frac{1}{2}var_t[\Delta s_{t+1}]=RP_t^{\$}+\lambda_t^{\$}. \tag{9}$$

where, $RP_t^{\$}=-cov_t\left(m_{t+1}^{\$},-\Delta s_{t+1}\right)$ is the risk premium the US investor requires for the exchange rate risk when investing in foreign bonds (i.e. the risk premium attached to the dollar appreciating).

Finally, we combine (5) and (9) to derive a cross-country restriction on the convenience yields imputed to Treasurys and the currency risk premia,

$$\lambda_t^*-\lambda_t^{\$}=RP_t^{\$}+RP_t^*-var_t[\Delta s_{t+1}]. \tag{10}$$

All else equal, an increase in λ_t^* has to be accompanied by a proportional increase in the risk premium U.S. investors ($RP_t^{\$}$) demand on foreign bonds, if we enforce the U.S. investor's Euler equation for foreign bonds. In an incomplete markets setting, the increase in the risk premium is a natural equilibrium outcome given that U.S. investors would increase their exposure to foreign exchange risk via the foreign bond carry trade in response to the expected depreciation of the dollar.[5]

1.3 Exchange rates and convenience yields

By forward iteration on eqn. (5), the level of exchange rates can be stated as a function of the interest rate differences, the currency risk premia and the future convenience yields (see Froot and Ramadorai, 2005, for a version without convenience yields).

Proposition 1. *The level of the nominal exchange can be written as:*

$$s_t = E_t \sum_{\tau=0}^{\infty} \lambda^*_{t+\tau} + E_t \sum_{\tau=0}^{\infty} (y^{\$}_{t+\tau} - y^*_{t+\tau}) - E_t \sum_{\tau=0}^{\infty} \left(RP^*_{t+j} - \frac{1}{2} Var_{t+j}[\Delta s_{t+j}] \right) + \bar{s}. \tag{11}$$

The term $\bar{s} = E_t[\lim_{j \to \infty} \ s_{t+j}]$ *which is constant under the assumption that the nominal exchange rate is stationary.*[6]

The exchange rate level is determined by yield differences, the convenience yields, and the currency risk premia. 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.

Alternatively, we can rewrite this equation as the sum of the convenience yield differentials, the fundamental yield differences, stripped of the convenience yields, and the risk premia:

$$s_t = E_t \sum_{\tau=0}^{\infty} (\lambda^*_{t+\tau} - \lambda^{\$}_{t+\tau}) + E_t \sum_{\tau=0}^{\infty} (\rho^{\$}_{t+\tau} - \rho^*_{t+\tau}) - E_t \sum_{\tau=0}^{\infty} \left(RP^*_{t+j} - \frac{1}{2} Var_{t+j}[\Delta s_{t+j}] \right) + \bar{s}. \tag{12}$$

Fundamentally, the exchange rate responds only to the difference in perceived convenience yields.

[5] There are some subtleties in this argument when markets are complete which we explain in the appendix. Alternatively, we could consider scenarios in which the U.S. Euler equation for foreign bonds does not hold for all investors. Suppose that the Euler equations for the U.S. investor in foreign bonds apply to a financial intermediary that is subject to financing frictions 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) on the importance of financial intermediary frictions is consistent with this mechanism. But note that even with such frictions, our equations linking foreign convenience yield valuations and the exchange rate remain valid.

[6] There is empirical support for the proposition that the real dollar exchange rate is stationary. Over the last 30 years, which is our data sample, inflation has been highly correlated and similar across developed countries, so that the nominal exchange rate is also plausibly stationary.

1.4 Convenience yields and CIP

Next, 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:

$$E_t\left[M_{t+1}^*\frac{F_t^1}{S_t}e^{y_t^\$}\right] = e^{-\lambda_t^{*,hedged}}, \qquad \lambda_t^{*,hedged} \geq 0, \tag{13}$$

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

$$x_t \equiv y_t^\$ + (f_t^1 - s_t) - y_t^* = -\lambda_t^{*,hedged}. \tag{14}$$

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 $\lambda_t^{*,hedged} > 0$, 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, $x_t < 0$.[7]

If the U.S. and foreign investors derive the same convenience yield from currency-hedged Treasurys, then C.I.P. is restored for the fundamental rates that are stripped of the convenience yields:

$$\rho_t^\$ + (f_t^1 - s_t) - \rho_t^* = \lambda_t^\$ - \lambda_t^{*,hedged}, \tag{15}$$

where we substituted for the U.S. Treasury yield in eq. (14).

1.5 Testing the model with nominal exchange rates

Our key assumption is that the convenience yields on the unhedged and hedged foreign investments in U.S. Treasury bonds are proportional to each other,

$$\lambda_t^* = \psi\left(\lambda_t^{*,hedged}\right) \Rightarrow \lambda_t^* = \psi(-x_t), \tag{16}$$

[7]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).

where ψ is a non-decreasing function of the hedged convenience yield: $\psi() \geq 0$, $\psi'() > 0$. This assumption allows us to make inference about the unobservable foreign convenience yield λ_t^* and thus test out model.

With this assumption, we arrive at two testable relations of our theory.

Proposition 2.

1. *The level of the nominal exchange can be written as:*

$$s_t = E_t \sum_{\tau=0}^{\infty} \psi(-x_{t+\tau}) + E_t \sum_{\tau=0}^{\infty} (y_{t+\tau}^{\$} - y_{t+\tau}^{*}) - E_t \sum_{\tau=0}^{\infty} \left(RP_{t+j}^{*} - \frac{1}{2} Var_{t+j}[\Delta s_{t+j}] \right) + \bar{s}. \tag{17}$$

2. *The expected log excess return to a foreign investor of a long position in Treasury bonds is increasing in the risk premium and the Treasury basis:*

$$E_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^{*} \right) = RP_t^{*} - \frac{1}{2} var_t[\Delta s_{t+1}] - \psi(-x_t) \tag{18}$$

1.6 Testing the model with real exchange rates

We have derived expressions for the equilibrium nominal exchange rate. These expressions are derived under the condition that the nominal exchange rate is stationary. When inflation rates are high, this assumption is likely violated. We next derive expressions for the real exchange rate, which may be stationary even if inflation rates are high.

Denote the log of the foreign and domestic price levels as p_t^* and $p_t^{\$}$, respectively. The real exchange rate is,

$$q_t = s_t + p_t^{\$} - p_t^{*}. \tag{19}$$

We substitute the real exchange rate expression, (19), into the earlier expressions for nominal exchange rates and rewrite to find:

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

$$q_t = E_t \sum_{\tau=0}^{\infty} \psi(-x_{t+\tau}) + E_t \sum_{\tau=0}^{\infty} (r_{t+\tau}^{\$} - r_{t+\tau}^{*}) - E_t \sum_{\tau=0}^{\infty} \left(RP_{t+j}^{*} - \frac{1}{2} Var_{t+j}[\Delta s_{t+j}] \right) + \bar{q}. \tag{20}$$

where, $\bar{q} = E_t[\lim_{j\to\infty} \ q_{t+j}]$ *is constant under the assumption that the real exchange rate is stationary. The terms* $r_t^{\$}$ *and* r_t^* *are the real interest rates, i.e.,* $y_t^{\$} - E_t[\Delta p_{t+1}^{\$}]$ *is the real dollar interest rate.*

We can also write the expected log excess return to a foreign investor of a long position in Treasury bonds in terms of the real exchange rate:

$$E_t[\Delta q_{t+1}] + \left(\left(y_t^{\$} - E_t[\Delta p_{t+1}^{\$}]\right) - \left(y_t^* - E_t[\Delta p_{t+1}^*]\right)\right) = RP_t^* - \frac{1}{2} var_t[\Delta s_{t+1}] - \psi(-x_t)$$

Note however that the expected change in the real exchange rate is equal to the expected change in the nominal exchange rate minus the difference between US and foreign expected inflation. Then, we can rewrite the LHS, canceling out the expected inflation terms, to equal $E_t[\Delta s_{t+1}] + \left(y_t^{\$} - y_t^*\right)$, to recover the same relation as (18).

To develop some intuition, we make simplifying assumptions to solve for the exchange rate at time t, q_t, explicitly as a function of the basis at time t, x_t. We assume that $\psi(-x_t) = -\phi x_t$ is linear. In addition, we assume that,

$$x_t = \varphi^* x_{t-1} + (1 - \varphi^*)\bar{x} + \epsilon_t^x, \quad \text{where} \quad 0 < \varphi^* < 1.$$

That is, the basis follows an AR(1) process with long-term mean of $\bar{x}$. We likewise assume that,

$$z_t \equiv r_t^{\$} - r_t^* - RP_t^* + \frac{1}{2} var_t[\Delta s_{t+1}]$$

also follows an AR(1) process with persistence parameter φ^z and long-term mean $\bar{z}$. We then evaluate the sum in (47). For the sum to be well defined $\phi\bar{x}$ must equal $\bar{z}$. Within a fully specified model, such a relation can be ensured by central bank behavior that targets a real exchange rate (see the examples in Engel and West (2005)). Then, the log of the real exchange is given by the following expression:

$$q_t = -\phi \frac{x_t}{1 - \varphi^*} + \frac{z_t}{1 - \varphi^z} + \bar{q}. \tag{21}$$

The quantitative effect of the dollar basis on the dollar depends on the persistence of the basis and the relative convenience yields derived from hedged and unhedged positions in Treasuries.

1.7 Convenience Yields on Foreign Bonds

We have so far assumed that foreign government bonds generate no convenience utility for its holders. This allowed us to most transparently explain how the convenience yield affects exchange rate determination. We now consider the realistic case when foreign bonds also carry a convenience yield. The notation is more cumbersome, but the economics follows naturally. We show that all of the prior results continue to hold with the twist that λ_t^* should be interpreted as the the convenience yield foreigners derive from holding U.S. Treasurys in excess of the convenience yields they derive from holding their own bonds, and $\lambda^\$$ should be interpreted as the convenience yield U.S. investors derive from U.S. Treasurys in excess of the yield derived from the foreign bonds. Finally, $\lambda_t^{*,hedged}$ should be interpreted as the convenience yield foreigners derive from holding Treasurys on a currency-hedged basis in excess of the yield derived from holding their own bonds.

To arrive at these findings, we enrich notation:

- $\lambda_t^{*,*}$ is the convenience yield of foreign investors for foreign bonds.
- $\lambda_t^{*,\$}$ is the convenience yield of foreign investors for U.S. Treasury bonds.
- $\lambda_t^{*,\$,hedged}$ is the convenience yield of foreign investors for currency-hedged U.S. Treasury bonds.
- $\lambda_t^{\$,*}$ is the convenience yield of U.S. investors for foreign bonds.
- $\lambda_t^{\$,\$}$ is the convenience yield of U.S. investors for U.S. Treasury bonds.

Appendix B provides the details of the derivations. Here we just highlight the important relations. First, we find that (see equation (36) of the Appendix),

$$E_t[\Delta s_{t+1}] + \left(y_t^\$ - y_t^*\right) + \frac{1}{2}var_t[\Delta s_{t+1}] = RP_t^* - \left(\lambda_t^{\$,*} - \lambda_t^{*,*}\right). \tag{22}$$

On the RHS in parentheses is the excess of the foreign investor's convenience yield for U.S. Treasury bonds over foreign government bonds. In our basic model, this term was λ_t^*, the foreign investor's convenience yield for U.S. Treasury bonds.

By forward iteration on equation (22), the level of exchange rates can be stated as a function of the interest rate differences, the currency risk premia and the future excess convenience yields:

Proposition 4. *The level of the nominal exchange can be written as:*

$$s_t = E_t \sum_{\tau=0}^{\infty}(\lambda_{t+\tau}^{\$,*} - \lambda_{t+\tau}^{*,*}) + E_t \sum_{\tau=0}^{\infty}(y_{t+\tau}^{\$} - y_{t+\tau}^{*}) - E_t \sum_{\tau=0}^{\infty}\left(RP_{t+j}^{*} - \frac{1}{2}Var_{t+j}[\Delta s_{t+j}]\right) + \bar{s}. \tag{23}$$

The term $\bar{s} = E_t[\lim_{j\to\infty} \; s_{t+j}]$ *which is constant under the assumption that the nominal exchange rate is stationary.*

A similar expression applies for the real exchange rate, following the derivations of the previous sections.

Last, we construct the basis measure:

$$x_t^{Treasury} \equiv y_t^{\$} + (f_t^1 - s_t) - y_t^* = -\left(\lambda_t^{\$,*,hedged} - \lambda_t^{*,*}\right) \tag{24}$$

The RHS is the (negative of) excess of the foreign investor's convenience yield for the hedged U.S. Treasury bond over the foreign bond. In the basic model this term was just the foreign investor's convenience yield for the hedged U.S. Treasury bond.

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

2.1 Data

We use two datasets, a panel from 1988 to 2017 and a longer single time series from 1970 to 2016 for the United States/United Kingdom pair.

The shorter panel is based on 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 use 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.[8]

[8] See Table 8 in the Appendix for detailed information. The Data Appendix contains information about data sources.

We construct the basis for each currency following (14). We do so using both government bond yields as measures of y_t as well as LIBOR rates as measures ($x_t^{Treasury}$ and x_t^{LIBOR}). In each quarter, we construct the mean and median basis across the panel of countries for that quarter. Figure 2 plots these series.

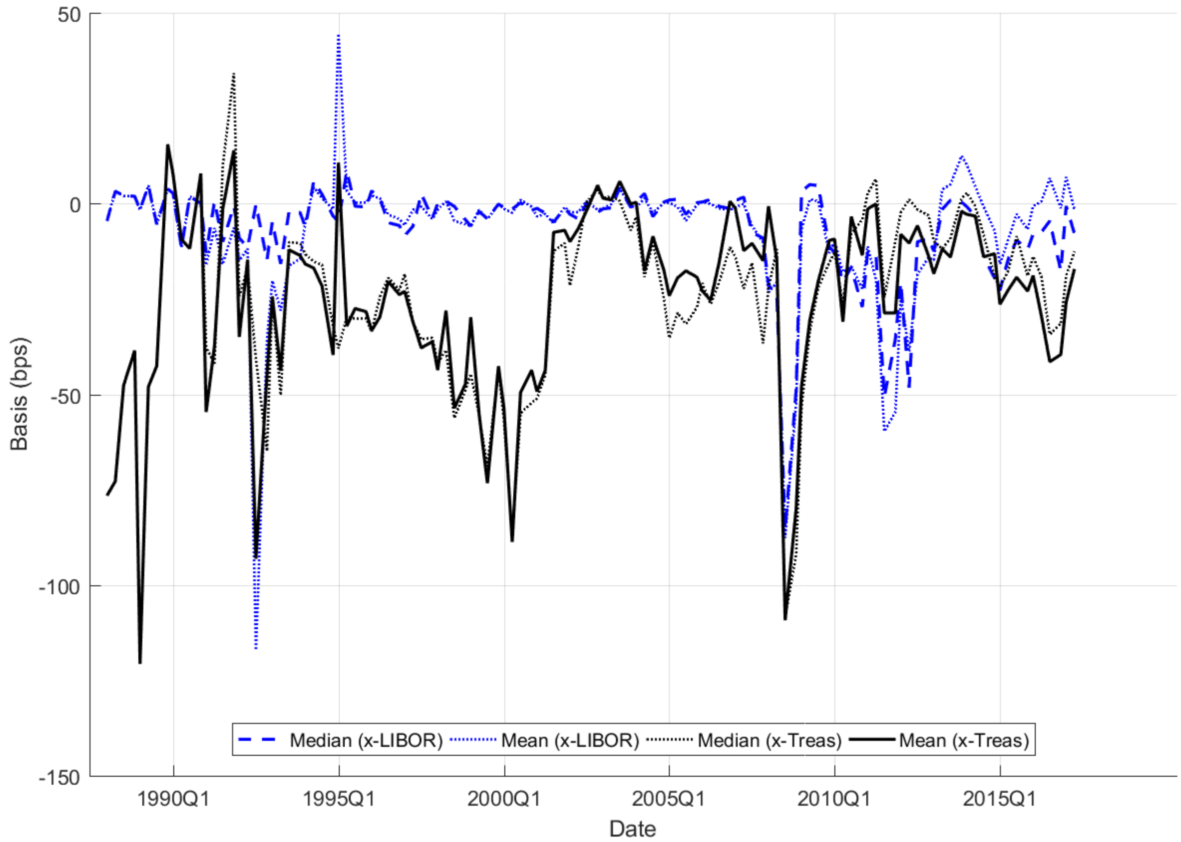

Figure 2: LIBOR and Treasury basis in basis points from 1988Q1 to 2017Q2. The maturity is one year.

The blue thick-dashed line corresponds to the median LIBOR basis. 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. 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 and the dashed black line is the median Treasury basis. *Unlike the LIBOR basis, the Treasury basis has always been negative and volatile.* Table 1 reports the time-series moments of the Treasury basis, the Libor basis, the 12M Treasury yield difference and the 12M forward discount. The average mean Treasury basis is -25 bps per annum, which means that foreign investors are willing to give up 25 bps per annum more for holding currency-hedged U.S. Treasurys than their own bonds. The standard deviation of the mean Treasury basis is 24 bps per quarter. In contrast, the average Libor basis is -7 bps.

Before the financial crisis, when the Libor basis was close to zero (-4 bps), the Treasury basis (-27 bps) is mostly due to this differential in the Treasury-Libor spreads. Foreign investors are willing to give up 27 bps. per annum on a currency-hedged basis to hold U.S. Treasurys, relative to holding their own bonds. This U.S. Libor-Treasury spread is 23 bps larger than its foreign counterpart. On average, U.S. investors were willing to give up 23 bps per annum more when holding a 12M U.S. Treasury than foreigners holding the foreign equivalent instrument. When the Libor basis is close to zero, the Treasury basis essentially is the U.S. convenience yield.

During and after the crisis, this U.S. Libor-Treasury spread is only 7 bps per annum higher than the foreign one, while the average Libor basis increases to -13 bps per annum. The implied U.S.-specific convenience yield on U.S. Treasurys (minus the foreign convenience yield on foreign bonds derived by foreign investors) is now only 7 bps. per annum, while foreign investors are willing to give up an extra 20 bps. per annum to hold U.S. Treasurys on a currency-hedged basis, again relative to holding foreign bonds.

Over the entire sample, the Treasury and Libor basis have a correlation of 0.36. This correlation increases to 0.56 after the financial crisis. The Treasury basis is negatively correlated (-0.27) with the Treasury yield difference and the forward discount.

Our second dataset covers the US/UK cross. This data begins in 1970Q1 and ends in 2016Q2. The daily data quality is poor, with many missing values and implausible spikes in the constructed basis from one day to the next. To overcome these measurement issues, we take the average of the available data for a given quarter as the observation for that quarter. We construct the Treasury basis in the same manner as described earlier. Figure 3 plots the resulting series. LIBOR rates do not exist back to 1971. The average US/UK Treasury basis is 0.84 bps per annum. On average, U.K. investors are close to indifferent between holding U.S. Treasurys on a currency-hedged basis and holding gilts. However, the standard deviation is 48 bps. per quarter. For comparison the figure also plots the mean basis from the cross-country panel. The two series track each other closely for the period where they overlap, but the US/UK basis is consistently higher than the panel basis. This may indicate that UK bonds also have a convenience yield. Additionally, the basis is above zero for frequently

Table 1: Summary Statistics of Cross-sectional Mean Basis and Interest Rate Difference

Table reports summary statistics in percentage points for the 12-M Treasury dollar basis $\overline{x}^{Treas}$, the Libor dollar basis $\overline{x}^{Libor}$, the 12M yield spread $y^{\$} - \overline{y^{*}}$, and the 12M forward discount $\overline{f-s}$ in logs. Table reports time-series averages, time-series standard deviations and correlations. Numbers reported are time-series moments of the cross-sectional means of the unbalanced Panel. 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. For each of these cross-sectional averages, we employ the same set of countries that are in the sample at time t.

	$\overline{x}^{Treas}$	$\overline{x}^{Libor}$	$y^{\$} - \overline{y^{*}}$	$\overline{f-s}$
	1988Q1−2017Q2			
mean	-0.25	-0.07	-0.45	-0.20
stdev	0.24	0.18	1.87	1.95
skew	-1.33	-3.08	-0.61	-0.29
x^{Treas}	1.00	0.36	-0.27	-0.39
x^{Libor}	0.36	1.00	0.47	0.40
$y^{US} - y^{*}$	-0.27	0.47	1.00	0.99
	1988Q1−2007Q4			
mean	-0.27	-0.04	-0.33	-0.05
stdev	0.26	0.16	2.25	2.34
skew	-0.93	-4.62	-0.69	-0.42
x^{Treas}	1.00	0.34	-0.31	-0.41
x^{Libor}	0.34	1.00	0.54	0.48
$y^{US} - y^{*}$	-0.31	0.54	1.00	0.99
	2008Q1−2017Q2			
mean	-0.20	-0.13	-0.64	-0.44
stdev	0.21	0.20	0.78	0.80
skew	-2.51	-1.78	0.16	0.09
x^{Treas}	1.00	0.56	0.00	-0.25
x^{Libor}	0.56	1.00	0.51	0.35
$y^{US} - y^{*}$	0.00	0.51	1.00	0.97

in the early part of the sample indicating that U.K. government bonds carried convenience yields.

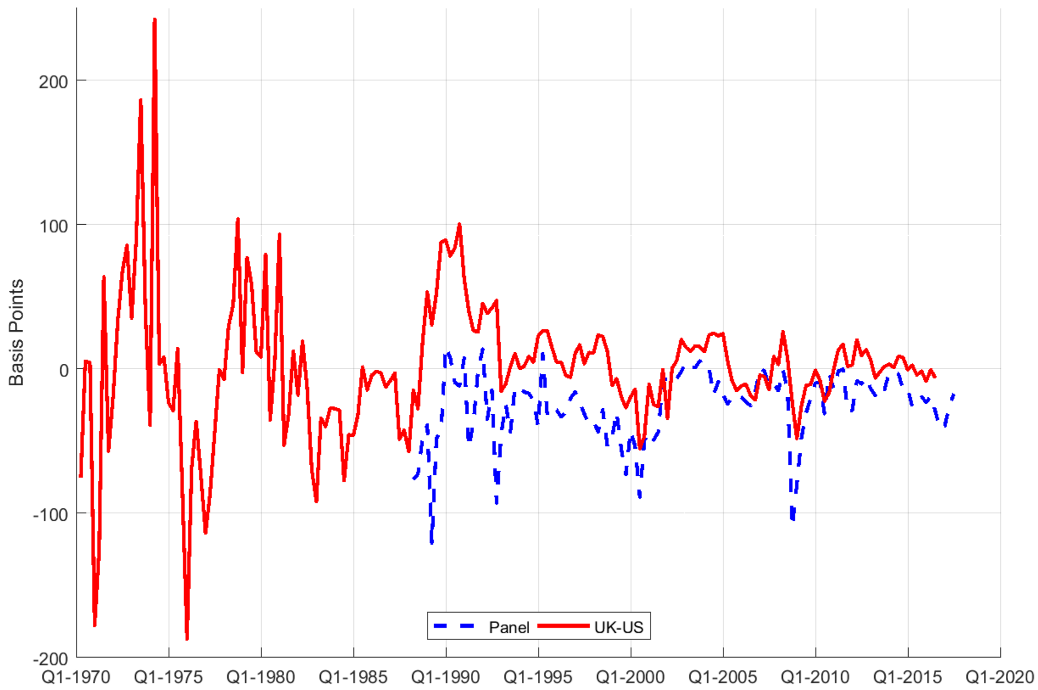

Figure 3: US/UK Treasury basis from 1970Q1 to 2017Q2 and the mean Treasury basis across the panel of countries, in basis points. The maturity is one year.

2.2 Treasury Basis and the Dollar

We denote the cross-sectional mean basis in the panel 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 $y_t^\$ - \overline{y}_t^*$.

We construct quarterly innovations in the basis by regressing $\overline{x}_t^{Treas} - \overline{x}_{t-1}^{Treas}$ on $\overline{x}_{t-1}^{Treas}, \overline{x}_{t-2}^{Treas}$ and $y_{t-1}^\$ - \overline{y}_{t-1}^*$ and computing the residual, $\Delta\overline{x}_t^{Treas}$. We then regress the contemporaneous quarterly change in the spot exchange rate, $\Delta\overline{s}_t \equiv \overline{s}_t - \overline{s}_{t-1}$, on this innovation. Table 2 reports the results. From columns (1), (3), (5), (6) and (8), we see that the innovation in the Treasury basis strongly correlates with changes in the exchange rate.

The sign is negative as predicted by Proposition 2. The result is also stable across the pre-crisis and post-crisis sample. From column (1), we see that a 10 bps decrease in the basis (or an increase in the foreign convenience yield) below its mean coincides with a 0.96% appreciation of the U.S. dollar.

To provide a further sense of magnitudes, note that the basis is mean reverting with an AR(1) coefficient of 0.53. A 10 basis point increase in the basis today implies that next quarter's basis will be about 5 basis points, and the following quarter will be 2.5 basis points, etc. Substituting these numbers into (21) and dividing by 4 to convert to quarterly values, the sum of these future increases is $\frac{10}{4} \times \frac{1}{1-0.53} = 5.3$. From (21), to rationalize the 0.96% appreciation we need a value of ϕ of $\frac{96}{5.3} = 18.2$. The basis is evidently very sensitive to changes in foreign investors' convenience valuation of US Treasury bonds. We return to the issue of the magnitude of ϕ later in the paper.

The R^2s 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). Our regressors account for 16.6% to 42.4% of the variation in the dollar's rate of appreciation. The LIBOR basis has explanatory power in the post-crisis sample as has been documented in prior work by Avdjiev et al. (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. We return to discuss the differential behavior of the LIBOR and Treasury basis in Section 3.2.

Column (3) of Table 2 includes the contemporaneous and the lagged innovation to the basis. This specification increases the R^2 to 23.5%. 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. The existence of momentum also indicates that ϕ is higher than the coefficient on the contemporaneous innovation, since a shock to the basis affects exchange rates for two quarters. We will evaluate the full impact via a Vector Autoregression in Section 2.4.

Column (4) of the table includes the innovation in the interest rate differential, $y^{\$} - y^{*}$, constructed analogous to the basis innovation. We see that increases in this interest rate spread has significant explanatory power in

Table 2: Average Treasury Basis and the USD Spot Nominal Exchange Rate

The dependent variable is the 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, $\Delta\bar{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation, the innovation in the LIBOR basis, and the innovation in the US-to-foreign interest rate differential. Data is quarterly. OLS standard errors in parentheses.

	1988Q1−2017Q2					1988Q1−2007Q4		2008Q1−2017Q2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\Delta\bar{x}^{Treas}$	-9.62		-9.70		-9.30	-8.52		-12.93	
	(2.05)		(1.95)		(1.70)	(2.58)		(3.18)	
$\Delta\bar{x}^{LIBOR}$		-2.47					2.79		-10.05
		(3.05)					(4.19)		(3.98)
Lag $\Delta\bar{x}^{Treas}$			-6.64		-6.21				
			(1.94)		(1.69)				
$\Delta(y^{\$} - \bar{y}^{*})$				3.70	3.59				
				(0.80)	(0.59)				
R^2	16.1%	0.6	23.5	20.4	42.4	12.2	0.6	32.1	15.4
N	117	117	116	117	116	80	80	37	37

our sample. A rise in the US rate relative to foreign appreciates the currency, which is what textbook models of exchange rate determination will predict (and is what equation (11) predicts). We include this covariate in column (5) along with the basis innovation. The R^2 rises to 42.4% and the coefficient estimates and standard errors are nearly unchanged. This is because the basis innovation and interest rate innovation are nearly uncorrelated in this sample (note: the levels are negatively correlated).

The FX markets in both spot and forward are large and liquid. Nevertheless, one may want to know the extent to which the relation we uncover stems from micro-structure order flow effects as in Evans and Lyons (2002) or Froot and Ramadorai (2005). Our theory does not involve these types of effects, and to test our theory ideally our data would reflect the mid of the bid and ask. Figure 4 presents a scatter plot of the change in the quarterly average log exchange rate against the change in the quarterly average basis. By computing a quarterly average, we average out bid-ask bounce and thus likely measure true mid-market prices. The relation we uncover is quite strong in this averaged data (in fact it is stronger than the end-of-quarter data of Table 2). Additionally, we can see from the graph that the variation reflected in the exchange rate is an order of magnitude larger than typical bid-ask spreads. The standard-deviation of exchange rate changes in log points

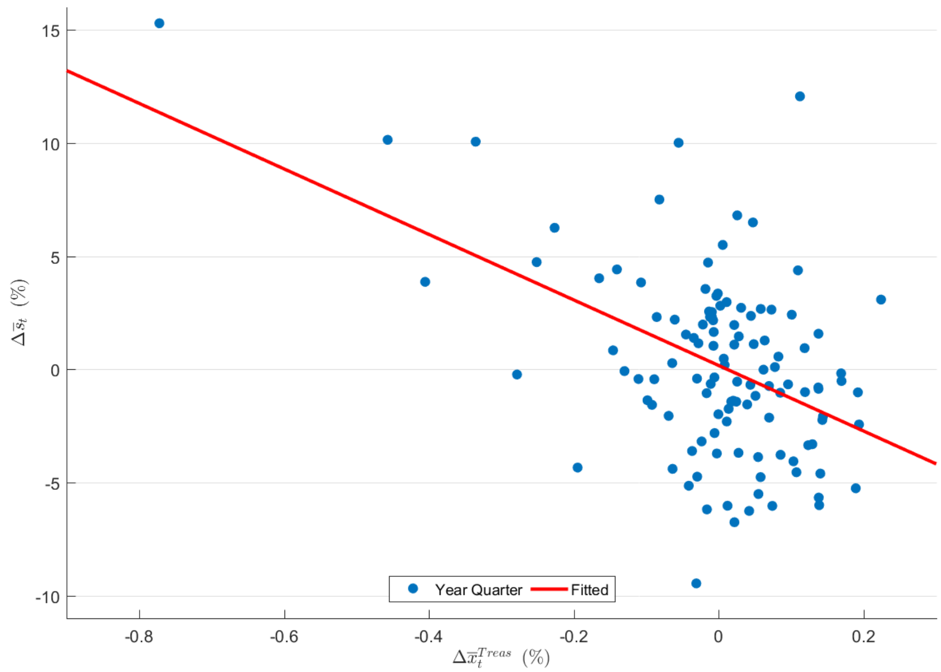

Figure 4: Scatter plot of changes in the log exchange rate, averaged over a quarter, against shocks to the quarterly average basis. Data is from 1988Q1 to 2017Q2. In red we plot the fitted regression line. The R^2 is 22.6% and the slope coefficient is -14.5 with a t-statistic of 5.77.

is 0.04, or 4%, which is well above typical bid-ask spreads. The standard-deviation of Treasury basis changes is 0.00134 (13.4 basis points). The slope coefficient on the fitted regression line of -14.5 implies that a one standard deviation change in the basis drives a 1.94% move in the exchange rate, which is also an order of magnitude larger than bid-ask spreads. Finally, the evidence in column (3) of Table 2 for momentum relates the lagged innovation in the basis to next quarter's change in the exchange rate. We also show predictability evidence in Table 4 and 5 relating the current basis to future changes in the exchange rate. Our results are evidently not driven by micro-structure effects.

We next turn to the US/UK data. The sample is longer, going back to 1970Q1. Figure 5 plots the real exchange rate in units of GBP-per-USD in red against the US/UK Treasury basis in blue. Both series are based on quarterly averaged data. We use the real exchange rate here because there are clear trends in the price levels of both countries in the 1970s and early 1980s that we would expect to enter exchange rate determination. It is evident that the two series are negatively correlated. Table 3 presents regressions analogous to that of Table

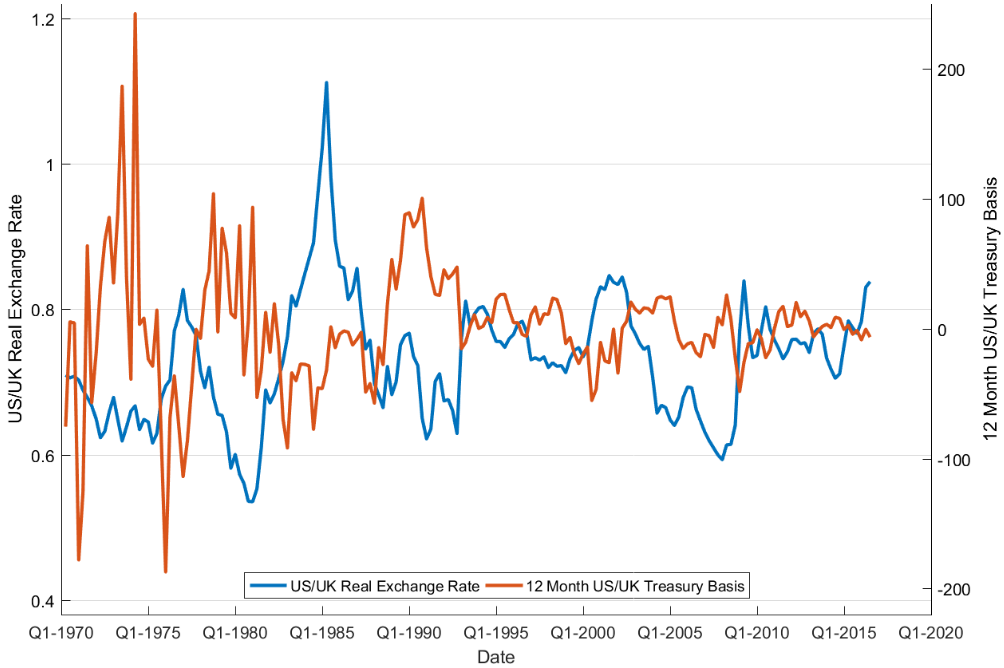

Figure 5: One-year maturity Treasury basis from 1970Q1 to 2017Q2 for US/UK, in basis points, and the real US/UK exchange rate.

2. We again see a strong relation between shocks to the basis and real exchange rate changes. The relation becomes stronger later in the sample. We think this is in part because of measurement issues with the basis during the 1970s. Note the spikey behavior of the basis in the 1970s in Figure 5. In the sample from 1990 onwards, the regression R^2 is 41.3% which is a remarkably strong fit. The coefficient in column (4) of the Table indicates that a 10 basis point increase in the basis is correlated with an 0.41% depreciation in the US dollar against the pound. The coefficients using the full sample are smaller than that of Table 2. For column (5), where the sample starts in 1990, the coefficient of -15.7 is similar in magnitude to our earlier estimates.

Column (2) considers the innovation in the interest rate differential as a regressor. In this sample in contrast to the cross-country sample, the interest rate differential has almost no explanatory power for the exchange rate. As noted in the introduction, the prior evidence linking interest rate changes and exchange rates is mixed and this is a clear example of this pattern. The source of the difference is the time period: If we focused on the sample from 1990 onwards, the interest rate differential has explanatory power similar to the result in Table 2.

Table 3: US/UK Treasury Basis and the Spot Real Exchange Rate

The dependent variable is the quarterly change in the quarterly-mean of the log of the spot USD/UK real exchange rate (quoted in GBP-per-USD). The independent variables are the innovation in the quarterly average Treasury basis, $\Delta\bar{x}^{Treas}$, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation, and the innovation in the US-UK interest rate differnetial. Data is quarterly. OLS standard errors in parentheses.

	1970Q1 - 2016Q2			1980Q1 - 2016Q2	1990Q1 - 2016Q2
	(1)	(2)	(3)	(4)	(5)
$\Delta\bar{x}^{Treas}$	-1.75		-1.76	-4.06	-15.7
	(0.75)		(0.82)	(1.63)	(2.27)
Lag $\Delta\bar{x}^{Treas}$	-1.87		-1.87	-5.32	-6.27
	(0.75)		(0.78)	(1.57)	(2.25)
$\Delta(y^{\$} - \bar{y}^{UK})$		-0.24	0.03		
		(0.39)	(0.4)		
R^2	5.5%	0.2	5.5	11.8	41.3
N	183	184	183	145	105

Column (3) includes basis innovations and interest rate differential innovations. The coefficients on the basis in column (3) are almost identical to those of column (1).

2.3 Future currency returns and the Treasury Basis

We turn to the second implication of Proposition 2, which can be read as a forecasting regression. A more negative x_t (high λ_t^*) today means that today's dollar exchange rate appreciates, which induces an expected depreciation over the next period.

Note that the LHS of equation (18) 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 term (RP), 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 2, 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 β_x should be positive. We run this regression using quarterly data, but compute the returns on the LHS as 3-months, one-year, two-year, and three-year returns. Because there is overlap in the observations, we compute heteroskedasticity and autocorrelation adjusted standard errors.

Table 4: Predicting Currency Excess Returns in the Panel

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, $(\bar{s}_{t+1} - \bar{s}_t) + (y_t^{\$} - \bar{y}_t^*)$, in units of log yield (i.e., 5% is 0.05). The independent variables are the average Treasury basis, $\bar{x}^{Treas}$, 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 $(y^{\$} - \bar{y}^*)$ in units of log yield. Data is quarterly from 1988Q1 to 2017Q2. Heteroskedasticity and autocorrelation adjusted standard errors in parentheses.

	3-month	1-year	2-year	3-year
$\bar{x}^{Treas}$	-25.58	6.55	11.89	15.36
	(10.30)	(7.84)	(4.38)	(3.29)
$y^{\$} - \bar{y}^*$	0.14	0.49	0.68	0.85
	(1.54)	(0.61)	(0.34)	(0.23)
Lag $\Delta\bar{x}^{Treas}$		-15.0	-14.6	-15.46
		(8.88)	(4.88)	(3.70)
R^2	10.4%	4.2	5.7	13.5
N	113	112	108	104

Table 4 presents the results. The first column reports results for the excess return over the next 3 months. Over this period we see that the coefficient on the basis is negative and statistically significant, in contrast to our theory. But there is a simple reason for this failure: we have seen earlier that there is momentum for one-quarter in the exchange rate. When the basis rises, the currency depreciates immediately, and continues to depreciate for another quarter, giving the negative relation between the basis and the one-quarter currency return. The next three columns consider longer horizons and include the lagged innovation in the basis to control for the momentum effect. The coefficient on $\bar{x}^{Treas}$ for these regressions is positive as suggested by our theory, with β_x significantly different from zero in the 2- and 3-year specification. Note that even the known predictor of carry trade returns, $y^{\$} - \bar{y}^*$, is only significant at the longer horizons. Last, we note that if we exclude the Treasury currency basis variables from the 3-year specification, the R^2 drops to 6%.

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 β_x is about 10 times larger than the magnitude of β_y indicating that the basis, although small, has a sizable effect on exchange rates. If we focus on the 2-year horizon, 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 1.2 % per annum over the next three years.

From equation (9) we see that the value of ϕ is equal to β_x for the 1-year horizon. But the β_x for 1-year is small and imprecisely estimated, likely because of the momentum effect we have found. A lower bound for ϕ is the estimate of β_x on the 2- and 3-year horizon regressions. This is a lower bound because a shock to the basis gradually reverses over time (we explore this formally in the next section), so that the returns in the 2nd and 3rd year are responding to a smaller value of the basis. This gives a lower bound for estimates of ϕ from 11.89 to 15.36. Our earlier estimate based on the coefficient in column (1) of Table 4 gave a value of 18.2, indicating consistency in these results.

Table 5: Predicting Currency Excess Returns in the US/UK Data

The dependent variable is the annualized excess return on a long position in US Treasuries and a short position in the UK Treasury bond, $(s_{t+1} - s_t) + (y_t^\$ - y_t^*)$, in units of log yield (i.e., 5% is 0.05). The independent variables are the Treasury basis, x^{Treas}, as log yield (i.e. 50 basis points is 0.005), the lagged value of the innovation in the Treasury basis, and the yield difference $(y^\$ - y^*)$ in units of log yield. Data is quarterly from 1970Q1 to 2016Q2. Heteroskedasticity and autocorrelation adjusted standard errors in parentheses.

	3-month	1-year	2-year	3-year
x^{Treas}	-5.85	2.17	7.22	11.92
	(2.43)	(3.23)	(2.52)	(1.89)
$y^\$ - y^*$	2.44	1.87	1.68	1.74
	(1.09)	(0.60)	(0.40)	(0.40)
Lag Δx^{Treas}		-5.97	-9.23	-11.31
		(3.53)	(3.32)	(2.45)
R^2	7.5%	8.1	11.1	24.6
N	183	180	176	172

Table 5 presents regressions for the US/UK data. The results are stronger but otherwise broadly in line with those reported in Table 4 . The first column shows the momentum effect for the first quarter whereby a high basis drives currency depreciation. As we extend the horizon, the coefficient on the basis turn positive as suggested by theory and become statistically different from zero. The magnitudes are also in line with those reported in Table 4.

2.4 Impact of Basis Shocks on the Real Exchange Rate

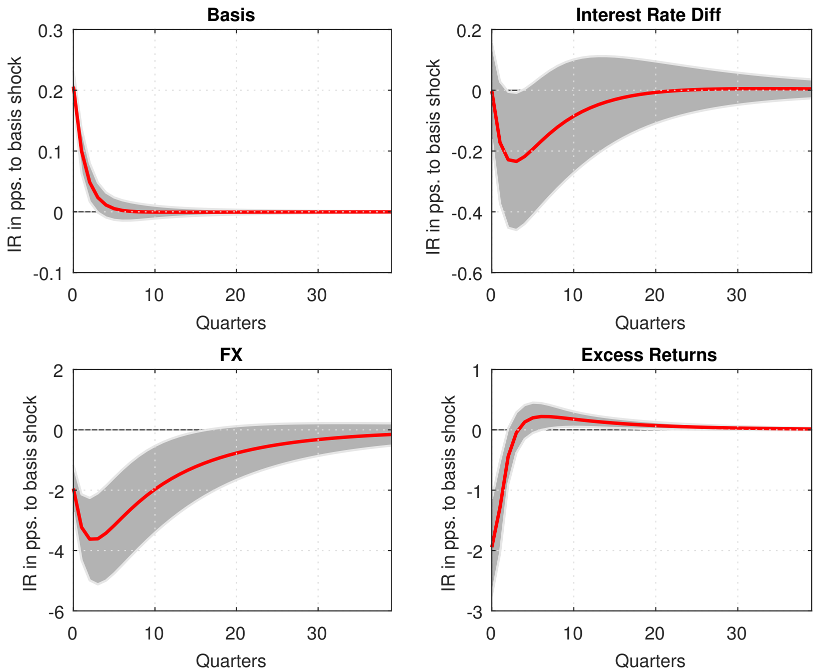

Figure 6: Dynamic Response to Treasury Basis Shocks: Panel. The red line plots the impulse response of a one-standard-deviation orthogonalized shock to the average Treasury basis on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. Standard errors were generated using 10,000 Monte Carlo simulations. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$.

We use a Vector Autoregression (VAR) to model the joint dynamics of the interest rate difference, the exchange rate and the Treasury basis. We estimate the VAR separately in both the panel and the US/UK data. For this exercise, we define the 12-month US real interest rate $r_t^{\$}$ as $y_t^{\$} - \pi_{t\to t+4}^{\$}$. The foreign real interest rate is similarly defined as $y_t^* - \pi_{t\to t+4}^*$. For the panel, we run a VAR with three variables: the basis, the real interest rate difference, and the log of the real exchange rate $\overline{x}_t^{Treas}$, $r_t^{\$} - \overline{r}_t^*$, and $\overline{q}_t$. The VAR includes one lag of all variables. We identified the VAR(1) as the optimal specification using the BIC. This specification assumes that the log of the real U.S. 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 the interest rate affect the exchange rate and the interest rate differential but not the basis, and shocks to the exchange rate only affect itself. This ordering implies that nominal and real exchange rates can respond instantaneously to all of the structural shocks. As we discuss, the evidence from the VAR provides support for interpreting our regression evidence causally: shocks to convenience yields drive movements in the exchange rate.

Figure 6 plots the impulse response from orthogonalized shocks to the basis. The top left panel plots the dynamic behavior of the basis (in units of percentage points), the top right panel plots the dynamic behavior of the interest rate difference (in percentage points), and the bottom left panel plots the behavior of the exchange rate (in percentage points). The pattern in the figure is consistent with the regression evidence from the Tables. An increase in the basis of 0.2% (decrease in the convenience yield) depreciates the real exchange rate contemporaneously by about 4% over two quarters. The finding that the depreciation persists over 2 quarters is consistent with the time-series momentum effect discussed earlier. Thus, the exchange rate exhibits classic Dornbusch (1976) overshooting behavior. Then there is a gradual reversal over the next 5 years over which the effect on the level of the dollar gradually dissipates. There is no statistically discernible effect of the basis on the interest rate differential. Finally, the bottom right panel plots the quarterly log excess return on a long position in dollars. Initially, the quarterly excess return drops, but after the first 2 quarters, it is higher than average for the next 15 to 18 quarters, consistent with higher expected returns on long positions in Treasurys.

Interestingly, once you add the basis shock, U.I.P. roughly holds for the dollar against this panel of currencies. Figure 7 plots the response to the interest rate shocks. The dollar appreciates in real terms in the same quarter by more than 100 basis points in response to a 100 bps increase in the U.S. yields above the foreign yields. Recently, Engel (2016) and Dahlquist and Penasse (2016) have documented that an increase in the short-term US interest rate initially causes the dollar to appreciate, but they subsequently depreciate on average. Once we allow for shocks to the basis, the initial appreciation effect disappears. The bottom right panel of the figure plots the excess return on the currency, and we see that this return is zero after the first quarter indicating that U.I.P. holds once we account for shocks to the basis.

Basis shocks account for a large fraction of the exchange rate forecast error variance, especially at longer horizons, as shown in Figure 8. At the one-quarter horizon, basis shocks account for more than 20% of the variance; this fraction increases to 60% at longer horizons. In contrast, the interest rate shocks account for less than 15% at all horizons. While the initial impact of a one-standard deviation interest rate shock on the dollar is similar to that of a one-standard deviation basis shock (roughly 2%), its effect does not initially build up and

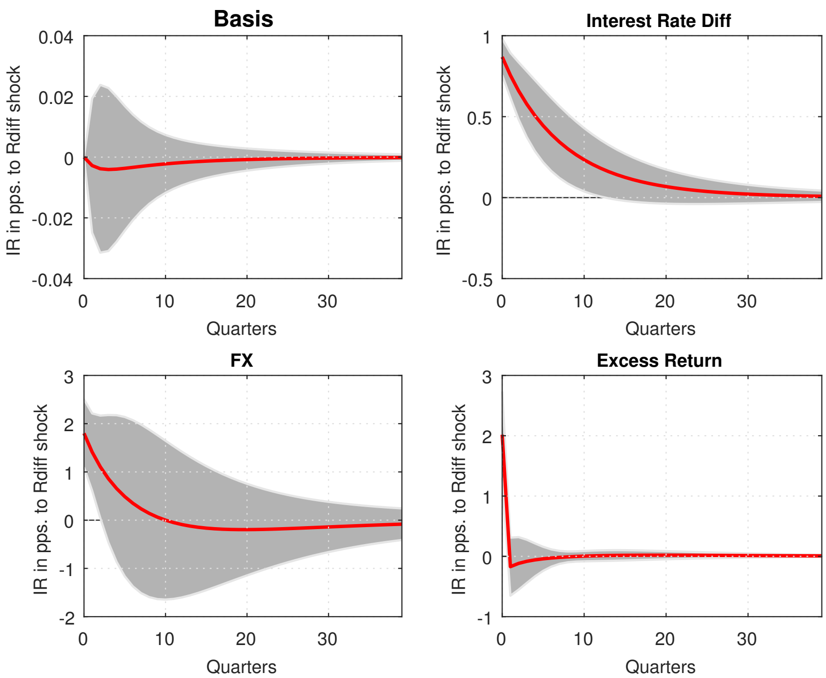

Figure 7: Dynamic Response to Rate Shocks: Panel. The red line plots the impulse response of a one-standard-deviation orthogonalized shock to the yield difference on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. Standard errors were generated using 10,000 Monte Carlo simulations. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$.

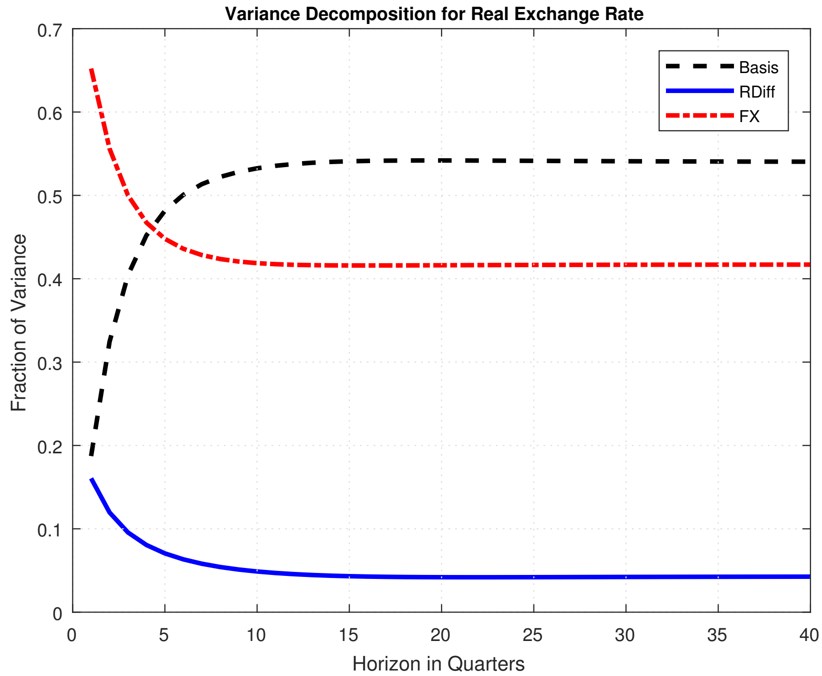

Figure 8: Variance Decomposition: Panel Plot of Variance of Forecast Error due to orthogonalized basis shocks, rate shocks and FX shocks against the forecast horizon. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\overline{x_t}, r_t^{\$} - \overline{r}_t^*, q_t$.

is much less persistent. Figure 12 in Section E of the Appendix reports all of the impulse responses.

Importantly, the results are not sensitive to switching the order of the basis and interest rate differential, indicating that we can plausibly interpret the relation between the basis and exchange rate causally. A shock to convenience yields moves both the basis and the exchange rate. We say this because we have allowed for other known determinants of the exchange rate, relative price levels and relative interest rates, and yet recover the same relation between the basis and the exchange rate. Figure 13 in the Appendix switches the ordering of the interest rate difference and the basis in the VAR. The impulse responses to a basis shock are nearly identical to those of Figure 7. The exchange rate falls a little under 4% over two quarters and then gradually reverts over the subsequent 2 years. Note that our finding that ordering does not matter need not have been the result. It occurs simply because the reduced form VAR innovations to the basis and the interest rate difference are only weakly correlated. Finally, the variance decomposition also looks independent of ordering.

Figure 9 turns to the US/UK longer time series. The variables included in the VAR are the basis, the interest rate differential and the log of the real exchange rate (GBP-per-USD). The impulse response patterns in this figure are similar to those documented in Figure 6, but have smaller magnitudes and are less persistent.

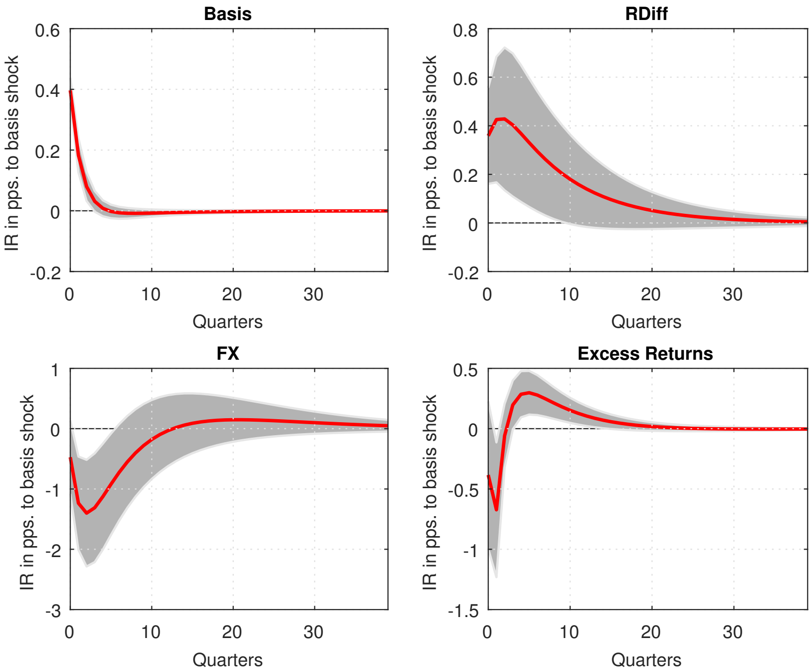

Figure 9: Dynamic Response to Treasury Basis Shocks: US/UK. The red line plots the impulse response of of a one-standard-deviation orthogonalized shock to the US/UK Treasury basis on the basis (top left panel), the real US/UK interest rate differential (top right panel), and the log real GBP-per-USD spot exchange rate (bottom left panel), as well as the quarterly excess return (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. Standard errors were generated using 10,000 Monte Carlo simulations. The VAR is estimated using a sample from 1970Q1 to 2016Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^{*}, q_t\right]$.

An increase in the basis of 40 basis points leads to a real depreciation in the dollar against the pound of about 1.2% over two quarters. Then, the effect gradually reverses out over 3 years. Figure 15 in the Appendix shows the impulse responses that obtain when we switch the ordering of the interest rate differences and the basis. The responses to the basis shock again look identical.

2.5 News decomposition

We denote $d_t = y_t^{US} - y_t^{UK}$. Define $\boldsymbol{z}_t' = \begin{bmatrix} x_t & d_t & s_t \end{bmatrix}$. We estimate following the first-order VAR for $\boldsymbol{z}_t$:

$$\boldsymbol{z}_t = \boldsymbol{\Gamma}_0 + \boldsymbol{\Gamma}_1 \boldsymbol{z}_{t-1} + \boldsymbol{a}_t,$$

where $\boldsymbol{\Gamma}_0$ is a 3-dimensional vector, $\boldsymbol{\Gamma}_1$ is a 3×3 matrix and $\boldsymbol{a}_t$ is a sequence of white noise random vector with mean zero and variance covariance matrix Σ. The variance covariance matrix is required to be positive definite.

The log of the currency excess return is given by $rx_t = s_t - s_{t-1} + d_{t-1}$. The realized risk premium component of the log currency excess return is the realized log excess return minus the convenience yield: $rp_t = rx_t - \phi \times x_{t-1}$. As a result, we can add an equation for the risk premium component of the log excess return to the VAR, and we end up with the following first-order VAR. Accordingly, we can define the state as the vector of demeaned variables: $\boldsymbol{y}_t' = \begin{bmatrix} \tilde{rp}_t & \tilde{x}_t & \tilde{d}_t & \tilde{s}_t \end{bmatrix}$. $\boldsymbol{y}_t$ follows a VAR(1) where

$$\boldsymbol{y}_t = \boldsymbol{\Psi}_1 \boldsymbol{y}_{t-1} + \boldsymbol{u}_t,$$

where $\boldsymbol{\Psi}_1$ is the 4×4 matrix defined in (45) in section D of the Appendix and $\boldsymbol{u}_t$ is the 4×1 vector of residuals defined above. When we use the real exchange rate q_t, we replace the interest rate difference d_t with the real interest rate difference $i_{t-1} = d_{t-1} - \pi_t^{US} + \pi_t^{UK}$. The log of the currency excess return is then $rx_t = q_t - q_{t-1} + i_{t-1} = s_t - s_{t-1} + d_{t-1}$; the realized inflation difference drops out from the excess return.

Our analysis follows Froot and Ramadorai (2005). From equation (20), changes in the exchange rate are due to changes in expectations of the basis (”convenience yield news”), changes in expectation of interest rate differentials (”cash flow news”), and changes in expectation of risk premia (” discount rate news”). We decompose exchange rate movements into those components and estimate how much each of the components account for variation in the exchange rate.

$$s_t = -\phi E_t \sum_{\tau=0}^{\infty} x_{t+\tau} + E_t \sum_{\tau=0}^{\infty} (y_{t+\tau}^{\$} - y_{t+\tau}^{*}) - E_t \sum_{\tau=0}^{\infty} \left(RP_{t+\tau}^{*} - \frac{1}{2} Var_{t+\tau}[\Delta s_{t+\tau+1}] \right) + \bar{s}. \quad (25)$$

We assume homoskedasticity of exchange rate changes.[9] As a result, the expression for the log of the exchange rate is given by:

$$s_t = -\phi E_t \sum_{\tau=0}^{\infty} x_{t+\tau} + E_t \sum_{\tau=0}^{\infty} d_{t+\tau} - E_t \sum_{\tau=1}^{\infty} rp_{t+\tau} + \bar{s}, \quad (26)$$

where we define $CY_t = -\phi E_t \sum_{\tau=0}^{\infty} x_{t+\tau}$ to be the convenience yield component, $CF_t = E_t \sum_{\tau=0}^{\infty} d_{t+\tau}$ to be the interest rate difference component, and the last part is the discount rate component: $DR_t = E_t \sum_{\tau=1}^{\infty} rp_{t+\tau}$.[10]

[9]Note that the risk premium is $RP_t = E_t rp_{t+1} + \frac{1}{2} Var[\Delta s_{t+1}]$. As a result, the discount rate component of the log exchange rate can be stated as: $E_t \sum_{\tau=0}^{\infty} RP_{t+\tau}^{*} = E_t \sum_{\tau=1}^{\infty} rp_{t+\tau} + \textit{constant} = E_t \sum_{\tau=1}^{\infty} (rx_{t+\tau} - \phi x_{t+\tau-1}) + \textit{constant}.$

[10]Using the VAR expressions, this simplifies to: $s_t = -\phi E_t \sum_{\tau=0}^{\infty} x_{t+\tau} + \sum_{j=0}^{\infty} \boldsymbol{e}_3 \boldsymbol{\Psi}_1^j \boldsymbol{y}_t - \sum_{j=1}^{\infty} \boldsymbol{e}_1 \boldsymbol{\Psi}_1^j \boldsymbol{y}_t + \bar{s}$.

From the definition of rp_t, it is easy to check that the current return innovation can be decomposed into a cash flow term, a discount rate term and a convenience yield term:

$$(E_t - E_{t-1})rp_t = (E_t - E_{t-1})\left[\sum_{j=0}^{\infty} d_{t+j}\right] - (E_t - E_{t-1})\left[\sum_{j=0}^{\infty} \phi x_{t+j}\right] - (E_t - E_{t-1})\left[\sum_{j=1}^{\infty} rp_{t+j}\right]$$

First, we compute the discount rate news from the VAR as:

$$N_{DR,t} = (E_t - E_{t-1})\left[\sum_{j=1}^{\infty} rp_{t+j}\right] = \boldsymbol{e}_1'\boldsymbol{\Psi}_1(I - \boldsymbol{\Psi}_1)^{-1}\boldsymbol{u}_t$$

Second, we can compute the CF or interest rate news from the VAR as:

$$N_{CF,t} = (E_t - E_{t-1})\left[\sum_{j=0}^{\infty} d_{t+j}\right] = \boldsymbol{e}_3'(I - \boldsymbol{\Psi}_1)^{-1}\boldsymbol{u}_t$$

Finally, what's left is the news about the convenience yields, which can be backed out of the discount rate and cash flow news:

$$N_{CY,t} = -(E_t - E_{t-1})\left[\sum_{j=0}^{\infty} \phi x_{t+j}\right] = -N_{CF,t} + N_{DR,t} + \boldsymbol{e}_1'\boldsymbol{u}_t$$

The top panel in Table 6 presents the results, estimated from the longest sample we have which is the US/UK nominal exchange rate from 1970 to 2016. We report results for different values of ϕ ranging from 5 to 20. Our estimates based on earlier regressions suggest a value of ϕ of between 15 and 20. At the $\phi = 15$ case, we see that convenience yield news (CY) accounts for 57% of the variance in quarterly exchange rates, in line with the high R^2 from earlier regressions. Interest rate news (CF) accounts for only a small component (13%) of the variance, while risk premium news (DR) accounts for a sizable component of 119%. Standard errors of our estimates are reported in square brackets in the table.

Note that the numbers in each row add up to 100% because shocks to these news components may be negatively correlated, as is apparent from the last two columns of the table. That is, the numbers in Table 6 should be read as the answer to the question: suppose we only had shocks to the basis, holding other components fixed – even though in practice such components will change when a basis shock arrives – how much variance

Table 6: News Decomposition of Real Exchange Rates Innovations

Decomposition of quarterly innovations in log of GBP/USD. Standard errors, reported in square brackets, were generated using 10,000 Monte Carlo simulations. The VAR is estimated using a sample from 1970Q1 to 2016Q2. The VAR(1) includes $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$.

ϕ	var(CY)	var(CF)	var(DR)	2cov(CY, CF)	-2cov(CY, DR)	-2cov(CF,DR)
5	0.06	0.13	0.82	0.09	-0.06	-0.04
	[0.03]	[0.06]	[0.21]	[0.07]	[0.09]	[0.13]
10	0.25	0.13	0.94	0.17	-0.37	-0.13
	[0.12]	[0.06]	[0.24]	[0.14]	[0.21]	[0.15]
15	0.57	0.13	1.19	0.26	-0.94	-0.21
	[0.28]	[0.06]	[0.31]	[0.21]	[0.45]	[0.19]
20	1.01	0.13	1.57	0.35	-1.75	-0.30
	[0.49]	[0.06]	[0.43]	[0.28]	[0.81]	[0.25]

in exchange rates will the basis shocks generate.

3 Discussion

3.1 How does the evidence identify demand for safe dollar assets?

We have argued that a specific form of capital flows, that for safe dollar assets, drives the value of the US dollar. This section further explains why our evidence supports this interpretation.

First, we construct the basis from the safest asset, the US Treasury bond, and document a relation between this basis and the dollar. It is evident that in the pre-crisis sample if we construct the basis from LIBOR rates, which reflect a bank deposit asset that is not as safe as Treasury bonds, there is no relation between the measured LIBOR basis and the dollar. By extension if we were to construct a basis say from the S&P500, measuring the expected return on the stock market, we conjecture that we will find no relation between the basis and the dollar. Second, the literature has found mixed evidence on the effectiveness of sterilized foreign exchange intervention (e.g. see the review article of Sarno and Taylor (2001)). That is, the data is not consistent with general capital account transactions, such as equity capital flows or central bank interventions, driving the exchange rate. Such an effect may be expected in the portfolio balance models of Kouri (1976), Hau and Rey (2004), and Gabaix and Maggiori (2015). Our evidence indicates that a specific form of the capital flow, that for safe US assets, drives the value of the US dollar.

Prior evidence for the special role of the US dollar in safe debt markets comes from quantity evidence based on non-government borrowings and investments. On the one hand, non-US borrowers tilt the denomination of their borrowings (loans, deposits, bonds) especially towards the US dollar. See Shin (2012) and Ivashina, Scharfstein and Stein (2015) on bank borrowing, Bräuning and Ivashina (2017) on loan denomination, and Bruno and Shin (2017) on corporate bond borrowing. On the other hand, there is also evidence that when foreign investors hold corporate bonds in currencies other than their own, they tilt their portfolios toward owning US dollar corporate bonds (see Maggiori, Neiman and Schreger (2017)). Note that this evidence does not pin down whether it is investors that especially want to own dollar assets, driving down the cost of borrowing in dollars and hence incentivizing firms and banks to borrow in dollars, or whether it is the reverse. That is, firms and banks especially want to borrow in dollars, are willing to pay higher returns on borrowing in dollars and hence attracting dollar international investors. Prices help resolve the issue. Our evidence is in favor of the former explanation, i.e., there is a special demand for US dollar safe assets driving down yields on these assets. The Treasury dollar basis is negative and declines in the basis appreciate the dollar.

Figure 10 provides further evidence that indicates that foreign investor's convenience yield is for safe dollar assets and not necessarily for safe U.S. Treasury bonds. We compute the basis for KfW bonds. KfW is a German issuer whose bonds are backed by the German government, so that they are near default free. KfW issues bonds in different currencies allowing us to compute the basis for the bonds of the same issuer, i.e., holding safety fixed, in different currencies. We compute the basis for KfW bonds using one-year yields on these bonds for Australia, Euro, UK, and Switzerland against the US. The yield data is from Bloomberg and corresponds to a fitted yield at the one-year maturity (one-year maturity bonds do not always exist). Clearly this measure is not as reliable as our Treasury basis measure which only uses information from traded instruments. Figure 10 plots the cross-country mean KfW basis and the Treasury basis (cross-country mean for the same countries) over a sample with daily data from 2011Q2 to 2017Q2. The two series have roughly the same magnitude and track each other closely. That is, the foreign hedged convenience yield on the U.S. dollar KfW bond closely matches the foreign hedged convenience yield on the U.S. Treasury bond.

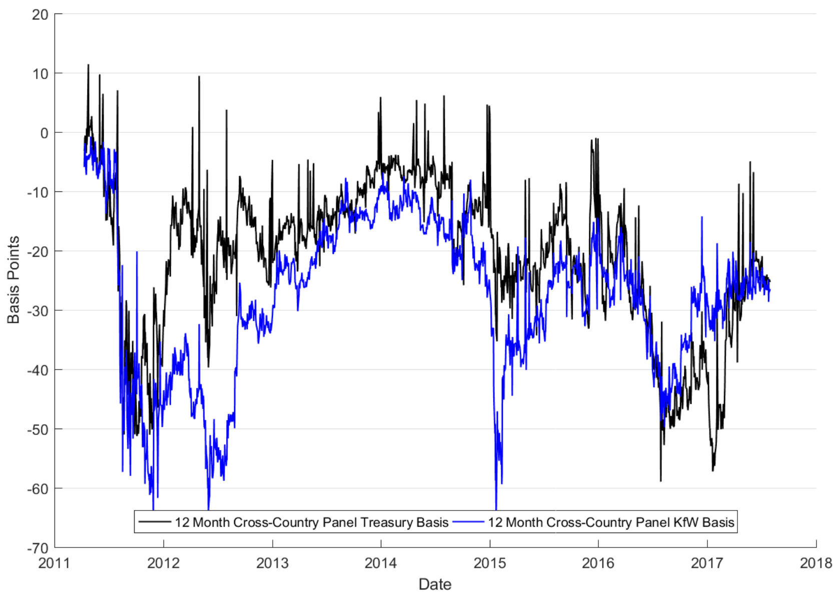

Figure 10: KfW and Treasury Basis, 2011Q2 to 2017Q2

These points also help to understand why our estimated value of ϕ is as high as 15. Recall that ϕ measures the ratio of the convenience yield a foreign investor assigns to an unhedged (dollar position) in the U.S. Treasury bond and a hedged back to local-currency investment in the U.S. Treasury bond. Our finding is that foreign investors prefer to hold the unhedged position. They particularly want to hold safe dollar bonds, as in the portfolio tilt evidence of Maggiori, Neiman and Schreger (2017).

3.2 Why does the LIBOR basis matter only after the crisis?

In US data, Krishnamurthy and Vissing-Jorgensen (2012) observe that there is a convenience yield on both Treasury bonds and other near-riskless private bonds such as bank deposits. They moreover show that some investors view near-riskless private bonds as partial substitutes for Treasury bonds. It is likely that this same property applies to foreign investors and helps explains the behavior of the LIBOR basis, as we argue in this section.

Consider the following adaptation of the model in Krishnamurthy and Vissing-Jorgensen (2012). Suppose foreign investors have preferences:

$$E\sum_{t=1}^{\infty}\beta^t u(C_t), \tag{27}$$

where C_t is the sum of an endowment c_t and convenience benefits:

$$C_t = c_t + \nu_t(\theta_t^P + \theta_t^B) + \mu_t(\theta_t^B).$$

Here θ_t^P are the market value of holdings of private safe assets and θ_t^B are the market value of holdings of Treasury bonds. The terms ν_t and μ_t are convenience benefits, satisfying $\nu_t, \mu_t > 0, \nu_t', \mu_t' \geq 0$ and, $\nu_t'', \mu_t'' \leq 0$. We make the further assumption that ν_t has a satiation point Θ where $\nu_t'(\Theta) = 0$. Private bonds and Treasury bonds are partial substitutes (the ν_t term), but Treasury bonds offer strictly more convenience benefits than private bonds (the μ_t term).

The first order condition for investing in a US Treasury bond that pays yield of $y_t^{\$}$ on a hedged basis is,

$$-u'(C_t) + \nu_t'(\theta_t^P + \theta_t^B) + \mu_t'(\theta_t^B) + E_t\left[\beta u'(C_{t+1})\frac{F_t^1}{S_t}e^{y_t^{\$}}\right] = 0$$

Defining $M_t^* = \beta\frac{u'(C_{t+1})}{u'(C_t)}$, we have that,

$$E_t\left[M_t^*\right]\frac{F_t^1}{S_t}e^{y_t^{\$}} = e^{-\lambda_t^{*,hedged}}$$

where,

$$e^{-\lambda_t^{*,hedged}} \approx 1 - \lambda_t^{*,hedged} = 1 - \nu_t'(\theta_t^P + \theta_t^B) - \mu_t'(\theta_t^B) \tag{28}$$

Relative to earlier equations (see (13)), we have now expressed the convenience yield in terms of asset quantities.

We follow the same steps for the investment in private bonds (bank deposits). The Euler equation gives (for private bond yield $y_t^{\$,P}$),

$$E_t\left[M_t^*\right]\frac{F_t^1}{S_t}e^{y_t^{\$,P}} = e^{-\lambda_t^{*,hedged,P}}$$

where,

$$e^{-\lambda_t^{*,hedged,P}} \approx 1 - \lambda_t^{*,hedged,P} = 1 - \nu_t'(\theta_t^P + \theta_t^B).$$

Note that ν_t' appears but μ_t' does not, because the private bonds only offer ν-type convenience benefits. Clearly the convenience yield on the Treasury bond investment is strictly higher than that of the private bond investment since $\nu_t' > 0$.

Next consider an unconstrained US investor ("bank") that also trades in the forward contract, F_t^1, as well as bank deposits in the US and foreign country and receives no convenience yield on either deposit. It follows that arbitrage requires,

$$E_t\left[M_t^*\right] \frac{F_t^1}{S_t} e^{y_t^{\$,P}} = E_t\left[M_t^*\right] e^{y_t^{*,P}},$$

where $y_t^{\$,P}$ and $y_t^{*,P}$ are the bank deposit rates in each country. We can simplify this expression to,

$$\frac{F_t^1}{S_t} e^{y_t^{\$,P}} = e^{y_t^{*,P}}, \tag{29}$$

which is the standard LIBOR-based CIP condition with no convenience yields. We immediately see that CIP must hold when computed using bank LIBOR deposit rates because of the possibility of bank arbitrage.

How can it be that the LIBOR basis is zero and yet foreign investors have convenience demand for US bank deposits? The answer is that in the equilibrium, unconstrained banks increase supply, θ_t^P, to the point where $\nu_t' = 0$ and hence $\lambda_t^{*,hedged,P} = 0$. But note that even at this large supply, we will have that,

$$\lambda_t^{*,hedged} = \lambda_t^{*,hedged,P} + \mu_t'(\theta_t^B) > 0.$$

This latter situation describes the pre-crisis equilibrium. The LIBOR basis is near zero; the Treasury basis is non-zero; and, only the Treasury basis has explanatory power for the dollar. (Following the logic we have provided, the missing arbitrageur here is the US Treasury, which could drive the Treasury basis to zero if it acted like an unconstrained bank.)

In the post-crisis equilibrium, banks are constrained hence both $\lambda_t^{*,hedged,P}$ and $\lambda_t^{*,hedged}$ are positive. Both are correlated with λ_t^* and both have explanatory power for the dollar, although as we have shown the Treasury basis has greater explanatory power.

This description of equilibrium relies on two assumptions: constraints on bank arbitrage in the post-crisis period; and, partial substitution between bank deposits and Treasury bonds. Du, Tepper and Verdelhan (2017) present compelling evidence in support of the first assumption. Here we provide support for the first assumption.

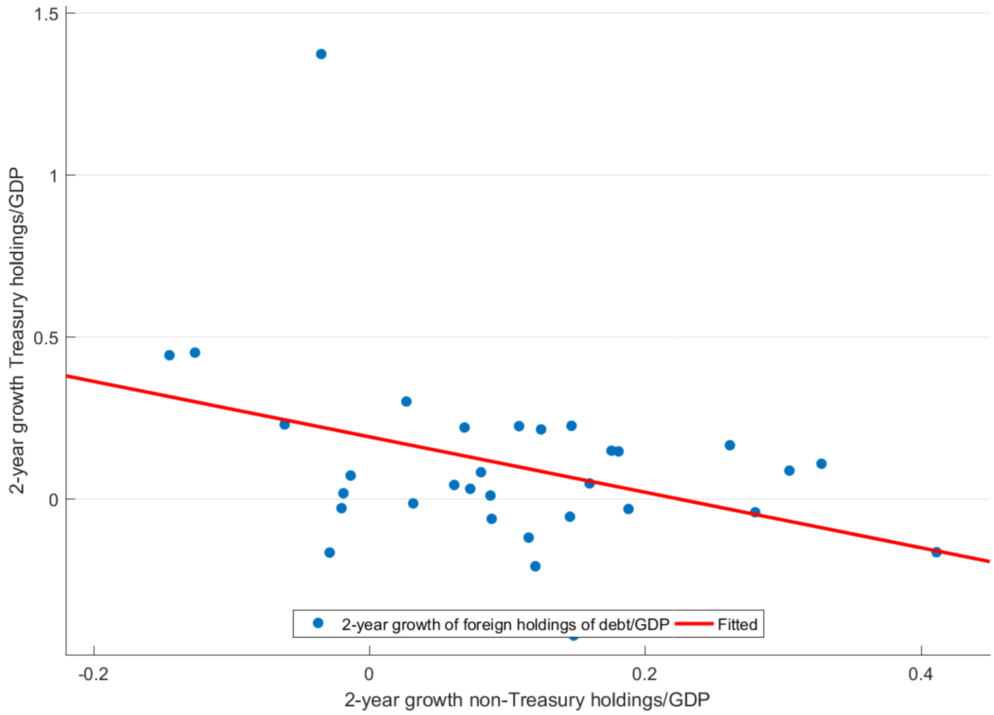

Figure 11: Growth in foreign holdings of Treasury and non-Treasury debt

Scatter plot of the 2-year growth in foreign holdings of US Treasury debt/GDP and non-Treasury US debt holdings/GDP. The sample is from 1951Q4 to 2015Q4. Growth rates are compute as log changes from Q4 to the Q4 2-year hence. Data is non-overlapping. The red line is the fitted regression line.

We show that as foreign private Treasury holdings fall, holdings of US dollar assets which are substitutes for Treasury bonds, in particular bank deposits, rise.[11] We obtain data on foreign holdings of U.S. Treasury bonds back to 1951Q4 from the Flow of Funds of the Federal Reserve. We also obtain data on U.S. assets which may be convenience substitutes.[12] We compute the ratio of this aggregate to US GDP to remove trends. We then correlate the 2-year growth rates in this non-Treasury debt series with the 2-year growth rates of the Treasury debt series, using Q4 to Q4 growth rates, with non-overlapping data. The sample is from 1951Q4 to 2015Q4. Figure 11 presents a scatter plot of the series, which are evidently negatively correlated (-0.37). The red line

[11]Maggiori, Neiman and Schreger (2017) document a special world demand for US dollar corporate bonds. We additionally show that the world bond demand is for safe US bonds by documenting that private safe bonds and safe Treasury bonds are portfolio substitutes for foreign investors.

[12]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.

in the figure is the fitted regression line. The regression coefficient is -0.85 with a $t-$statistic of 2.20 and the regression R^2 is 14%.

3.3 Time-variation in the demand for safe assets

Table 7: The Basis and Interest Rate Spreads

We regress the quarterly average Treasury basis, $\overline{x}^{Treas}$, on a number of US money market spreads and the US to foreign government bond interest rate differential. The spreads and interest rate differential are constructed as the quarterly average of the indicated series. Data is from 1988Q1 to 2017Q2 for the regressions with 118 observations and 2001Q4 to 2017Q2 for the regressions with 63 observations. OLS standard errors in parentheses.

	(1)	(2)	(3)	(4)	(5)	(6)
US 6-month OIS−T-bill	0.13					
	(0.18)					
US 6-month LIBOR−OIS		-0.40			-0.44	
		(0.034)			(0.027)	
US 6-month LIBOR−T-bill			-0.47			-0.43
			(0.045)			(0.044)
$y^{\$} - \overline{y}^{*}$				-0.047	-0.07	-0.029
				(0.01)	(0.01)	(0.007)
R^2	1%	69.5	48	16.7	82.9	54
N	63	63	118	118	63	118

Table 7 provides some statistics on the covariates of the Treasury basis. In the first column, we regress the basis on the OIS-T-bill spread which is a measure of the liquidity premium on Treasury bonds. Note that the basis is negative on average (see Figure 2). There is little relation between the basis and OIS-Tbill. The second column instead uses the spread between LIBOR and OIS which is a measure of the riskiness of banks. This spread is strongly negatively related to the basis. When the LIBOR-OIS spread rises, the basis goes more negative, as in the crisis episode pictured in Figure 1. The R^2 of the regression is 69.5% indicating a flight-to-quality pattern in the foreign demand for safe Treasury bonds. OIS is only available from 2001. Column (3) reports the correlation with the LIBOR-Tbill spread which we can construct to the start of our sample in 1988. There is a strong negative relation between the spread and the basis, and we learn from columns (1) and (2) that the relation is likely due to the LIBOR-OIS component of this spread (note also that the coefficient on LIBOR-OIS is quite similar to the coefficient on LIBOR-T-bill). Column (4) includes the spread between US interest rates and the mean foreign interest rate. When US rates are high relative to foreign rates, the basis is more negative. We have run specifications where we include both US and foreign interest rates, and subject to the caveat that these rates do move together, the correlation seems to be driven by the US interest rate and not the foreign rate. Column (5) and (6) include both the LIBOR spread and the US to world interest rate differential. The explanatory power for the basis is largely driven by the LIBOR spread as one can see when comparing the R^2 in columns (5) and (6) to those in columns (3) and (4).

4 Conclusion

Safe asset demand for U.S. Treasurys drive a wedge between currency-hedged Treasury yields and foreign yields, even in the absence of other financial market frictions. These wedges have explanatory power for variation in the dollar exchange rate, consistent with our convenience yield theory, in data from 1970 to 2017. Our convenience yield theory of exchange rates, which departs from existing theories, imputes a central role to international flows in Treasury debt and related dollar safe asset markets in exchange rate determination. The spot exchange rate of a safe asset currency will reflect the cumulative value of all future convenience yields.

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A Convenience Yields in Complete Markets

We follow the approach of Backus, Foresi and Telmer (2001). Consider the Euler equations (1) and (7) for the US and foreign investor when investing in the foreign bond. To satisfy these Euler equations, we conjecture an exchange rate process that satisfies,

$$M_t^{\$}\frac{S_t}{S_{t+1}} = M_t^*.$$

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:

$$\Delta s_{t+1} \quad = \quad m_t^{\$} - m_t^*. \tag{30}$$

Next consider the pair of Euler equations, (2) and (8), which apply to investments in the US bond that gives a convenience yield. We conjecture an exchange rate process that satisfies,

$$M_t^* e^{\lambda_t^*} \frac{S_{t+1}}{S_t} = M_t^{\$} e^{\lambda_t^{\$}}.$$

Log-linearizing this expression, we find:

$$\Delta s_{t+1} \quad = \quad \left(m_t^{\$} - m_t^*\right) + \left(\lambda_t^{\$} - \lambda_t^*\right) \tag{31}$$

It is evident that (30) and (31) cannot both be satisfied in an equilibrium unless $\lambda_t^* = \lambda_t^{\$}$. But note that in the case, convenience yields have no impact on exchange rates.

How is equilibrium restored when $\lambda_t^* \neq \lambda_t^{\$}$? The answer is that one of the Euler equations must be an inequality. There are many ways this may happen. Portfolio choices could be at a corner. For example, if foreign investors assign a positive convenience yield to their own foreign bonds, while US investor do not, then the US investor Euler equation does not apply to foreign bonds. Alternatively, if foreign convenience demand for US bonds is so high that US investors do not own US bonds, then the US Euler equation does not apply to US bonds. Another possibility are forms of market segmentation. Suppose that some US investors derive convenience value from US bonds, but these same investors do not own foreign bonds. Other US investors do not derive convenience value from US bonds, and these investors do own foreign bonds. In these cases as well, one of the Euler equations we have posited is an inequality.

B Convenience Yields on Foreign Bonds

B.1 Convenience yields and exchange rates

This section allows for a convenience yield on foreign bonds. Foreign investors price foreign bonds denominated in foreign currency, and the foreign investor's Euler equation is given by:

$$E_t \left(M_{t+1}^* e^{y_t^*}\right) = e^{-\lambda^{*,*}}. \tag{32}$$

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,

$$E_t \left(M_{t+1}^* \frac{S_{t+1}}{S_t} e^{y_t^{\$}}\right) = e^{-\lambda_t^{\$,*}}, \qquad \lambda_t^* \geq 0. \tag{33}$$

Next, we use these pricing conditions to derive an expression linking the exchange rate and the convenience yield. We assume that $m_t^* = \log\ M_t^*$ and $\Delta s_{t+1} = \log \frac{S_{t+1}}{S_t}$ are conditionally normal. Then, (32) can be rewritten as,

$$E_t \left(m_{t+1}^*\right) + \frac{1}{2} Var_t \left(m_{t+1}^*\right) + y_t^* + \lambda_t^{*,*} = 0, \tag{34}$$

and (33) as,

$$E_t\left(m_{t+1}^*\right)+\frac{1}{2}Var_t\left(m_{t+1}^*\right)+E_t[\Delta s_{t+1}]+\frac{1}{2}var_t[\Delta s_{t+1}]+y_t^{\$}+\lambda_t^{\$,*}-RP_t^*=0. \tag{35}$$

Here $RP_t^*=-cov_t\left(m_{t+1}^*,\Delta s_{t+1}\right)$ is the risk premium the foreign investor requires for the exchange rate risk when investing in US bonds. We combine these two expressions to find that the expected return in levels on a long position in dollars earned by a foreign investor is given by:

$$E_t[\Delta s_{t+1}]+\left(y_t^{\$}-y_t^*\right)+\frac{1}{2}var_t[\Delta s_{t+1}]=RP_t^*-\lambda_t^{\$,*}+\lambda_t^{*,*}. \tag{36}$$

B.2 U.S. demand for foreign bonds

The U.S. investor's Euler equation when investing in the foreign bond is:

$$E_t\left(M_{t+1}^{\$}\frac{S_t}{S_{t+1}}e^{y_t^*}\right)=e^{-\lambda_t^{*,\$}}. \tag{37}$$

We also assume that U.S. investors derive a convenience yield when investing in U.S. Treasurys:

$$E_t\left(M_{t+1}^{\$}e^{y_t^{\$}}\right)=e^{-\lambda_t^{\$,\$}}. \quad \lambda_t^{\$,\$}\geq 0. \tag{38}$$

$\lambda_t^{\$}$ is asset-specific. An increase in the U.S. investor's convenience yield lowers U.S. Treasury bond yields, holding the SDF fixed: $y_t^{\$}=\rho_t^{\$}-\lambda_t^{\$,\$}$, where $\rho_t^{\$}=-\log E_t\left(M_{t+1}^{\$}\right)$.

We assume log-normality and rewrite these equations to derive an expression for the carry trade return,

$$\left(y_t^*-y_t^{\$}\right)-E_t[\Delta s_{t+1}]+\frac{1}{2}var_t[\Delta s_{t+1}]=RP_t^{\$}-\lambda_t^{*,\$}+\lambda_t^{\$,\$}. \tag{39}$$

where, $RP_t^{\$}=-cov_t\left(m_{t+1}^{\$},-\Delta s_{t+1}\right)$ is the risk premium the US investor requires for the exchange rate risk when investing in foreign bonds (i.e. the risk premium attached to the dollar appreciating).

Finally, we combine (36) and (39) to derive a cross-country restriction on the convenience yields imputed to Treasurys and the currency risk premia,

$$(\lambda_t^{\$,*}-\lambda_t^{*,*})-(\lambda_t^{\$,\$}-\lambda_t^{*,\$})=RP_t^{\$}+RP_t^*-var_t[\Delta s_{t+1}]. \tag{40}$$

B.3 Exchange rates and convenience yields

By forward iteration on eqn. (36), the level of exchange rates can be stated as a function of the interest rate differences, the currency risk premia and the future convenience yields (see Froot and Ramadorai, 2005, for a version without convenience yields):

$$s_t=E_t\sum_{\tau=0}^{\infty}(\lambda_{t+\tau}^{\$,*}-\lambda_{t+\tau}^{*,*})+E_t\sum_{\tau=0}^{\infty}(y_{t+\tau}^{\$}-y_{t+\tau}^*)-E_t\sum_{\tau=0}^{\infty}\left(RP_{t+j}^*-\frac{1}{2}Var_{t+j}[\Delta s_{t+j}]\right)+\bar{s}. \tag{41}$$

The term $\bar{s}=E_t[\lim_{j\to\infty}\ s_{t+j}]$ which is constant under the assumption that the nominal exchange rate is stationary.

B.4 Hedged Treasury positions

Next, 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:

$$E_t \left[M_{t+1}^* \frac{F_t^1}{S_t} e^{y_t^\$} \right] = e^{-\lambda_t^{\$,*,hedged}}, \quad \lambda_t^{\$,*,hedged} \geq 0, \tag{42}$$

where F_t^1 denotes the one-period forward exchange rate, expressed in units of foreign currency per dollar. We combine this equation with (32) to derive the Treasury-based dollar basis:

$$x_t \equiv y_t^\$ + (f_t^1 - s_t) - y_t^* = \lambda_t^{*,*} - \lambda_t^{\$,*,hedged}. \tag{43}$$

If the U.S. and foreign investors derive the same convenience yield from currency-hedged Treasurys, then C.I.P. is restored for the fundamental rates that are stripped of the convenience yields:

$$\rho_t^\$ + (f_t^1 - s_t) - \rho_t^* = (\lambda_t^{\$,\$} - \lambda_t^{\$,*,hedged}), \tag{44}$$

where we substituted for the U.S. Treasury yield in eq. (43).

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 9), 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 10), 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 8: 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 9: 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 10: 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

D Campbell-Shiller Decomposition

We denote $d_t = y_t^{US} - y_t^{UK}$. Define $\boldsymbol{z}_t' = \begin{bmatrix} x_t & d_t & s_t \end{bmatrix}$. We estimate following the first-order VAR for $\boldsymbol{z}_t$:

$$\boldsymbol{z}_t = \boldsymbol{\Gamma}_0 + \boldsymbol{\Gamma}_1 \boldsymbol{z}_{t-1} + \boldsymbol{a}_t,$$

where $\boldsymbol{\Gamma}_0$ is a 3-dimensional vector, $\boldsymbol{\Gamma}_1$ is a 3×3 matrix and $\boldsymbol{a}_t$ is a sequence of white noise random vector with mean zero and variance covariance matrix Σ. The variance covariance matrix is required to be positive definite.

The log of the currency excess return is given by $rx_t = s_t - s_{t-1} + d_{t-1}$. The realized risk premium component of the log currency excess return is the realized log excess return minus the convenience yield: $rp_t = rx_t - \phi \times x_{t-1}$. As a result, we can add an equation for the risk premium component of the log excess return to the VAR, and we end up with the following first-order VAR:

$$\begin{bmatrix} rp_t \\ x_t \\ d_t \\ s_t \end{bmatrix} = \begin{bmatrix} \gamma_0 \\ \Gamma_{0,1} \\ \Gamma_{0,2} \\ \Gamma_{0,2} \end{bmatrix} + \begin{bmatrix} 0 & \Gamma_{3,1} - \phi & \Gamma_{3,2} + 1 & \Gamma_{3,3} - 1 \\ 0 & \Gamma_{1,1} & \Gamma_{1,2} & \Gamma_{1,3} \\ 0 & \Gamma_{2,1} & \Gamma_{2,2} & \Gamma_{2,3} \\ 0 & \Gamma_{3,1} & \Gamma_{3,2} & \Gamma_{3,3} \end{bmatrix} \begin{bmatrix} rp_{t-1} \\ x_{t-1} \\ d_{t-1} \\ s_{t-1} \end{bmatrix} + \begin{bmatrix} a_{3,t} \\ a_{1,t} \\ a_{2,t} \\ a_{3,t} \end{bmatrix} \tag{45}$$

When we use the real exchange rate q_t, we replace the interest rate difference d_t with the real interest rate difference $i_{t-1} = d_{t-1} - \pi_t^{US} + \pi_t^{UK}$. The log of the currency excess return is then $rx_t = q_t - q_{t-1} + i_{t-1} = s_t - s_{t-1} + d_{t-1}$; the realized inflation difference drops out from the excess return.

Accordingly, we can define the state as the vector of demeaned variables: $\boldsymbol{y}_t' = \begin{bmatrix} \tilde{rp}_t & \tilde{x}_t & \tilde{d}_t & \tilde{s}_t \end{bmatrix}$. $\boldsymbol{y}_t$ is a VAR process of order 1

$$\boldsymbol{y}_t = \boldsymbol{\Psi}_1 \boldsymbol{y}_{t-1} + \boldsymbol{u}_t,$$

where $\boldsymbol{\Psi}_1$ is the 4×4 matrix defined in (45) and $\boldsymbol{u}_t$ is the 4×1 vector of residuals defined above.

Our analysis follows Froot and Ramadorai (2005). From equation (20), changes in the exchange rate are due to changes in expectations of the basis (”convenience yield news”), changes in expectation of interest rate differentials (”cash flow news”), and changes in expectation of risk premia (” discount rate news”). We decompose exchange rate movements into those components and estimate how much each of the components account for variation in the exchange rate.

$$s_t = -\phi E_t \sum_{\tau=0}^{\infty} x_{t+\tau} + E_t \sum_{\tau=0}^{\infty} (y_{t+\tau}^{\$} - y_{t+\tau}^{*}) - E_t \sum_{\tau=0}^{\infty} \left(RP_{t+\tau}^{*} - \frac{1}{2} Var_{t+\tau}[\Delta s_{t+\tau+1}] \right) + \bar{s}. \tag{46}$$

We assume homoskedasticity of exchange rate changes.[13] As a result, the expression for the log of the exchange rate is given by:

$$s_t = -\phi E_t \sum_{\tau=0}^{\infty} x_{t+\tau} + E_t \sum_{\tau=0}^{\infty} d_{t+\tau} - E_t \sum_{\tau=1}^{\infty} rp_{t+\tau} + \bar{s}, \tag{47}$$

[13]Note that the risk premium is $RP_t = E_t rp_{t+1} + \frac{1}{2} Var[\Delta s_{t+1}]$. As a result, the discount rate component of the log exchange rate can be stated as: $E_t \sum_{\tau=0}^{\infty} RP_{t+\tau}^{*} = E_t \sum_{\tau=1}^{\infty} rp_{t+\tau} + constant = E_t \sum_{\tau=1}^{\infty} (rx_{t+\tau} - \phi x_{t+\tau-1}) + constant.$

where we define $CY_t = -\phi E_t \sum_{\tau=0}^{\infty} x_{t+\tau}$ to be the convenience yield component, $CF_t = E_t \sum_{\tau=0}^{\infty} d_{t+\tau}$ to be the interest rate difference component, and the last part is the discount rate component: $DR_t = E_t \sum_{\tau=1}^{\infty} rp_{t+\tau}$.[14]

E Impulse Responses

[14]Using the VAR expressions, this simplifies to: $s_t = -\phi E_t \sum_{\tau=0}^{\infty} x_{t+\tau} + \sum_{j=0}^{\infty} \boldsymbol{e}_3 \boldsymbol{\Psi}_1^j \boldsymbol{y}_t - \sum_{j=1}^{\infty} \boldsymbol{e}_1 \boldsymbol{\Psi}_1^j \boldsymbol{y}_t + \bar{s}$.

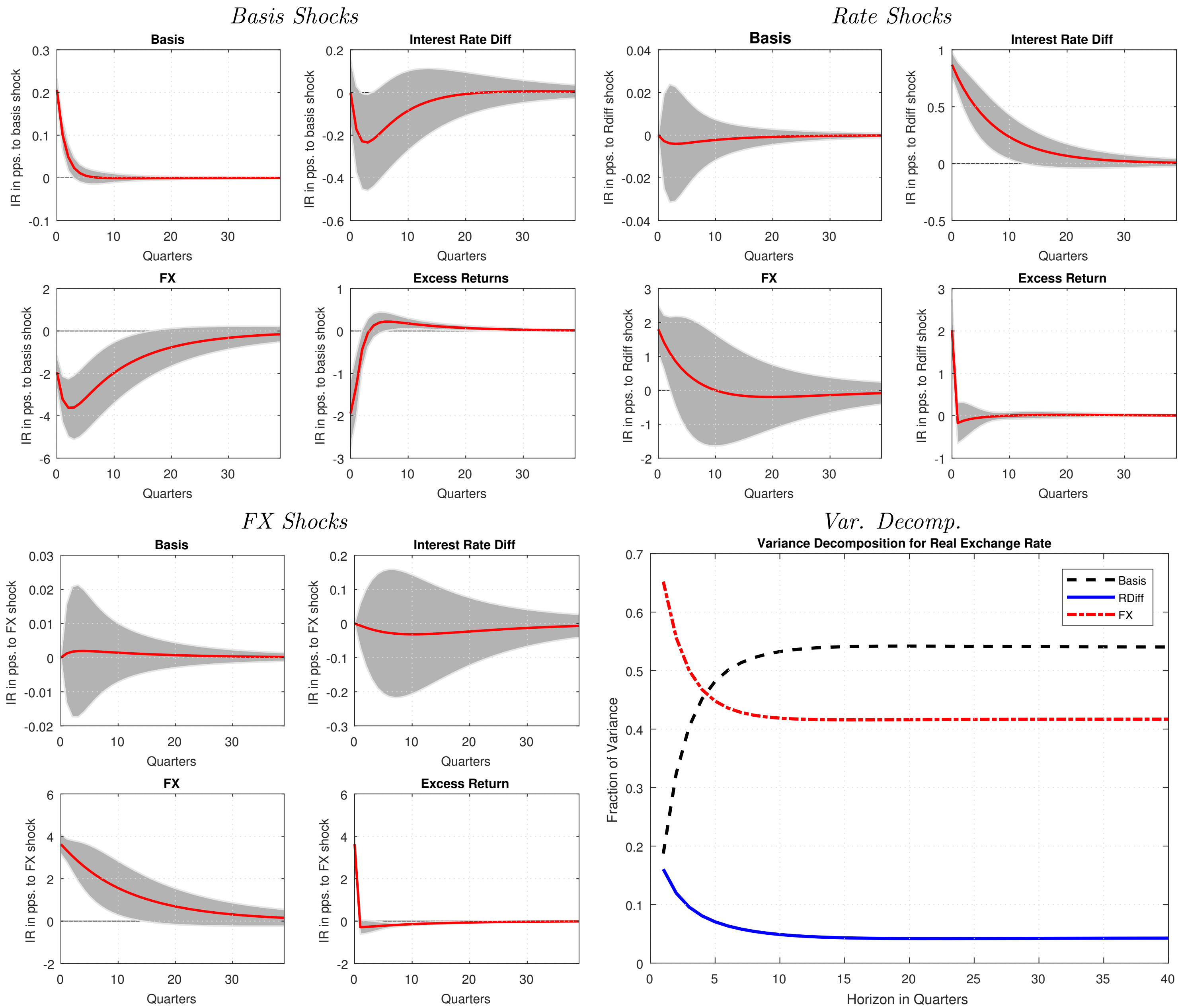

Figure 12: Panel Impulse Responses. The red line plots the impulse response of an orthogonalized one-standard-deviation shock on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$.

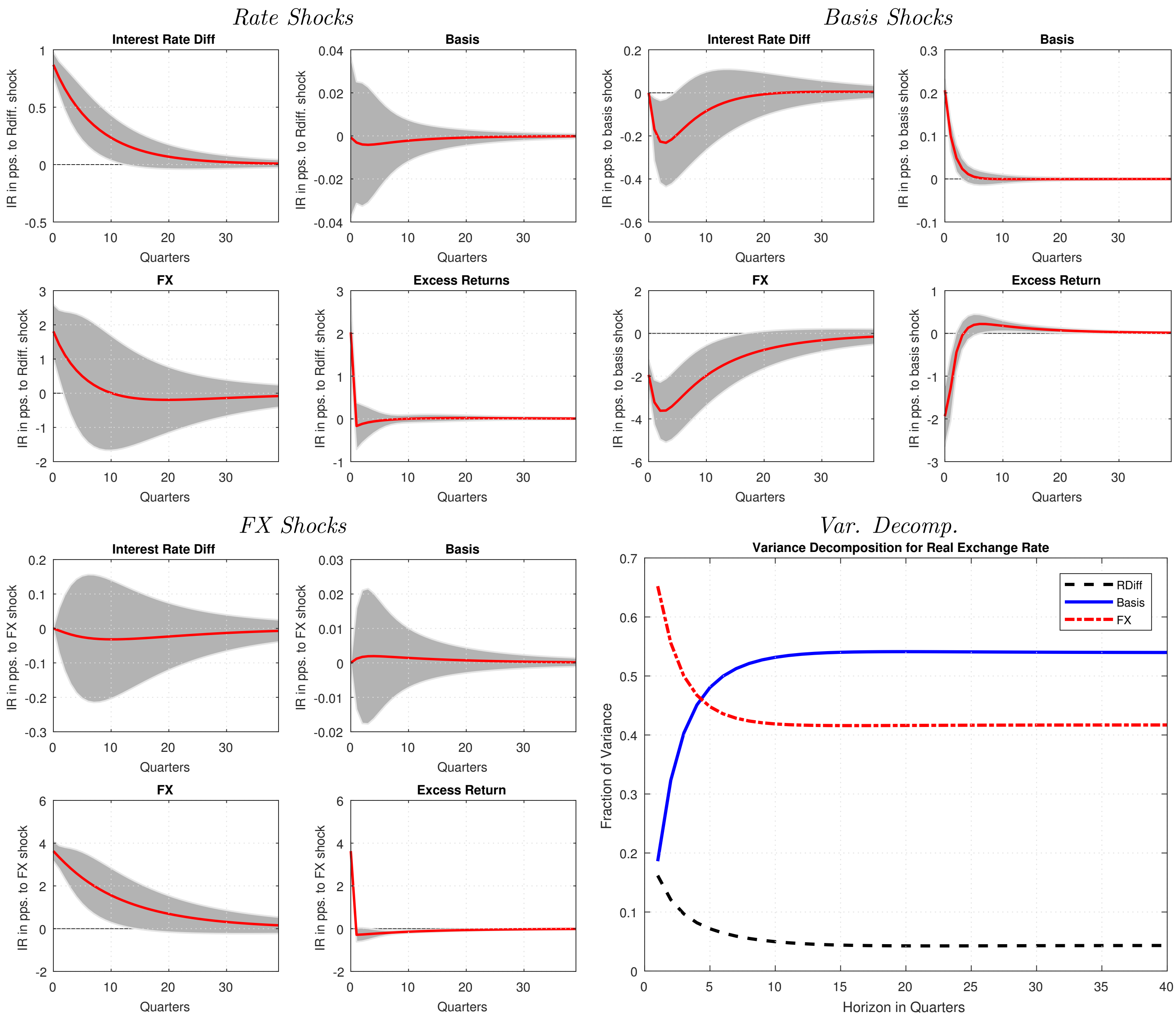

Figure 13: Panel Impulse Responses: Alternate Ordering. The red line plots the impulse response of an orthogonalized one-standard-deviation shock on the basis (top left panel), the real interest rate differential (top right panel), the log real spot exchange rate (bottom left panel), and the quarterly log excess return on a long position in dollars (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. The VAR is estimated using a sample from 1988Q1 to 2017Q2. The ordering is $\left[r_t^{\$} - \overline{r}_t^{*}, \overline{x}_t, q_t\right]$.

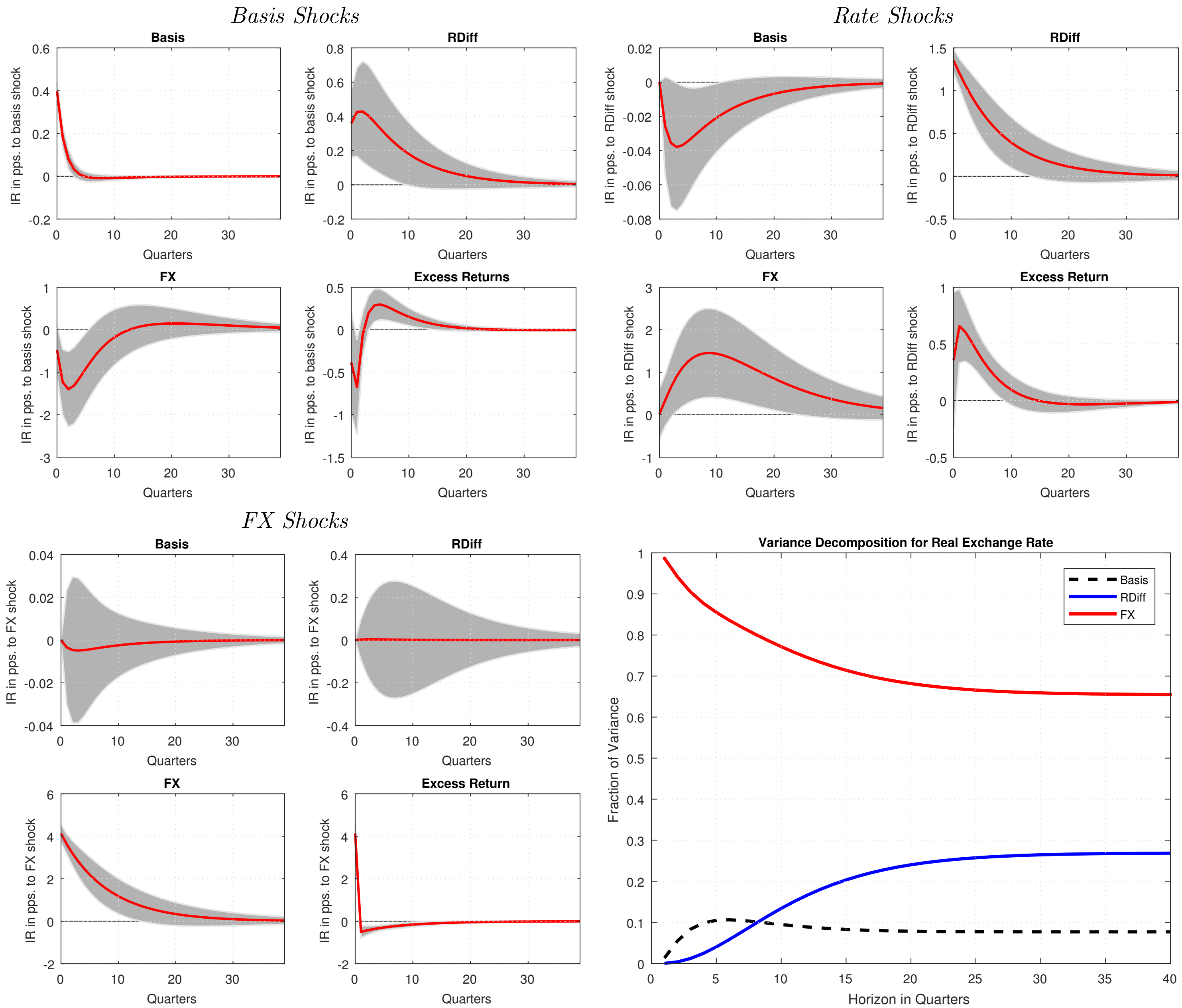

Figure 14: UK/US Impulse Responses. The red line plots the impulse response of of a one-standard-deviation orthogonalized shock to the US/UK Treasury basis on the basis (top left panel), the real US/UK interest rate differential (top right panel), and the log real GBP-per-USD spot exchange rate (bottom left panel), as well as the quarterly excess return (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. The VAR is estimated using a sample from 1970Q1 to 2016Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^{*}, q_t\right]$.

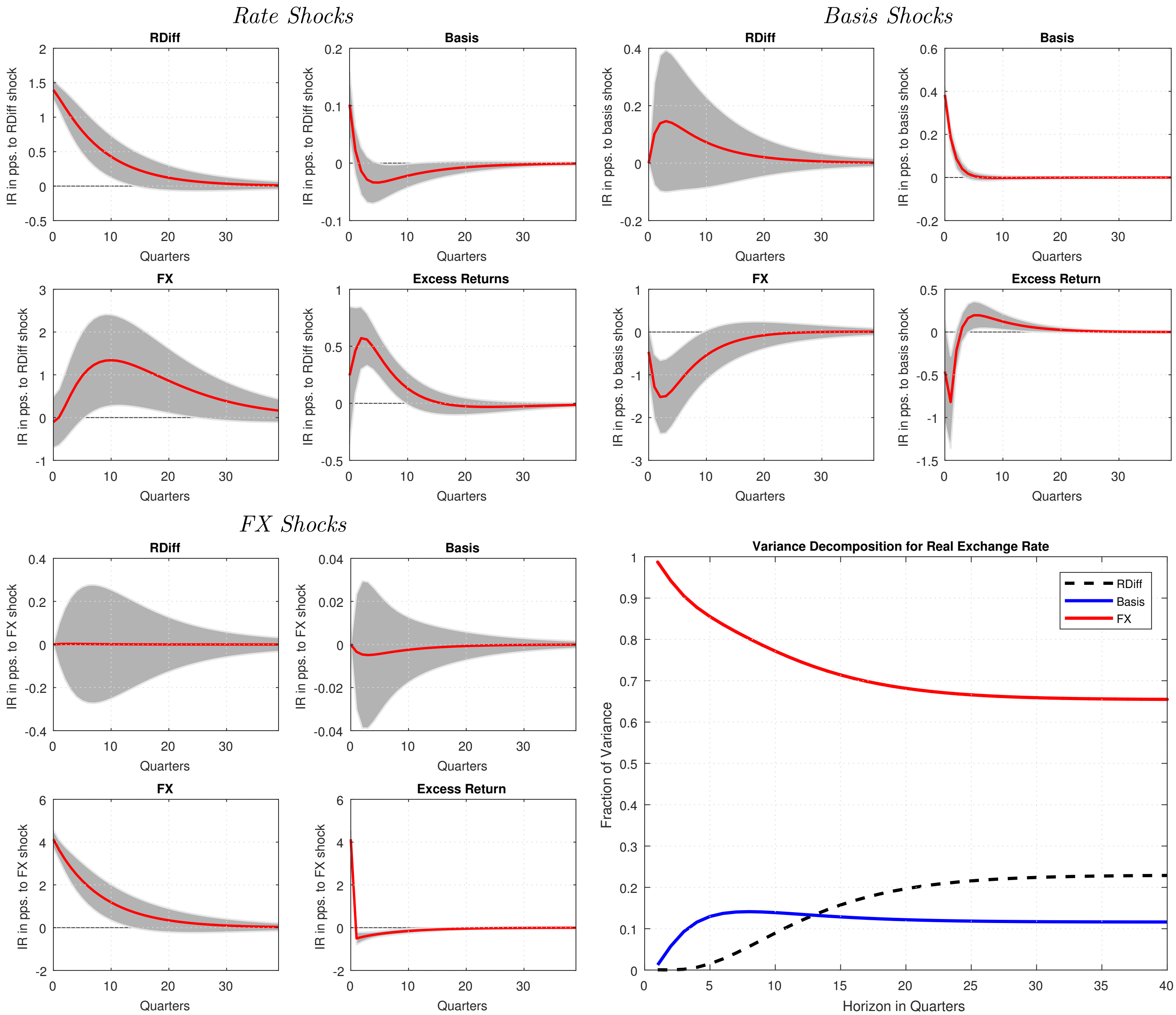

Figure 15: UK/US Impulse Responses: Alternate Ordering. The red line plots the impulse response of of a one-standard-deviation orthogonalized shock to the US/UK Treasury basis on the basis (top left panel), the real US/UK interest rate differential (top right panel), and the log real GBP-per-USD spot exchange rate (bottom left panel), as well as the quarterly excess return (bottom right panel). The units for the y-axis are in percentage points. The grey areas indicates 95% confidence intervals. The VAR is estimated using a sample from 1970Q1 to 2016Q2. The ordering is $\left[\overline{x}_t, r_t^{\$} - \overline{r}_t^*, q_t\right]$.