Risk Free Interest Rates

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Abstract

We estimate risk free interest rates unaffected by the convenience yield on safe assets. We infer them from risky asset prices without relying on any specific model of risk. Our rates imply a term structure of convenience yields with maturities ranging from 1 month to 2.5 years, available at a minutely frequency. We find that between 2004 and 2018 the convenience yield on government bonds is about 40 basis points, is larger below 3 months maturity, and grows substantially during periods of financial distress. We also estimate the high frequency response of convenience yields to monetary policy and quantitative easing. Convenience yields respond most strongly to central bank policy in the depths of the financial crisis and are reduced by both conventional and unconventional monetary stimulus. We further construct a convenience-yield-free measure of covered interest parity deviations and document a significant role for convenience yields in the predictability of bond returns.

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1. Introduction

Arguably the most important variable in financial economics is the interest rate on a risk free investment. In frictionless asset pricing models it measures the time value of money: the required return for receiving a riskless payoff in the future instead of the present. To measure investors' willingness to take risk, the returns on risky assets are compared to this risk free interest rate, where the difference in average returns is conventionally interpreted as the compensation for bearing the asset's risk, i.e., the asset's risk premium. As a consequence, any attempt to measure either the risk or time preferences of investors from asset prices requires a precise estimate of the risk free interest rate.

Empirically, the yield or interest rate on safe assets (such as government bonds) are often used to measure the time value of money. However, a recent literature has provided evidence that the interest rates on safe assets are driven in part by other forces (Krishnamurthy and Vissing-Jorgensen (2012), Nagel (2016)). Safe assets earn a so-called "convenience yield" that reflects the ease with which they can be traded by uninformed agents, posted as collateral, or perform other roles similar to that of money.[1] Thus, the yield on a money-like asset is below that of the yield implied by the time value alone, reflecting the liquidity and collateral value of such assets.

In this paper, we estimate risk free rates that are unaffected by the convenience yield on safe assets by inferring them from the prices of risky assets. Our empirical measurement is motivated by the fact that in several recent asset pricing models with frictions, risky assets do not earn a convenience yield while safe assets do.[2] As a result, under the assumptions of these models, a risk free rate inferred from risky asset prices should be a pure measure of the time value of money. This has at least two applications. First, the spread between our rates and the observed yields on safe assets precisely estimate the safe assets' convenience yields. Second, our method identifies the correct risk free rate to which a frictionless model (in which risk free rates are determined by the time value of money alone) should be calibrated.

We infer our benchmark rates from the put-call parity relationship for European-style options and show robustness using other implied risk free rates, such as those inferred from

[1]See Gorton and Pennacchi (1990) among several others.

[2]E.g. Frazzini and Pedersen (2014), Stein (2012), Caballero and Farhi (2018), and Diamond (2018).

a storage arbitrage in the market for precious metals futures. We find that the convenience yields on government bonds equals about 40 basis points on average over 2004-2018, with a relatively flat average term structure across maturities beyond 3 months, and a somewhat higher average below 3 months. We further find that the convenience yield is strongly time varying and grows substantially during periods of financial distress.

Our estimated rates have four main advantages over existing rates in the literature. First, because our rates are entirely inferred from risky asset prices, they are free of the convenience yield on safe assets. In contrast, the common practice in the literature is to compute spreads between the yields on various safe assets, which only identifies *differences* in convenience yields on more and less money-like assets. Second, the high-frequency nature of our option quotes allows us to estimate our interest rates minute by minute, while many existing rates only have data available at lower (e.g. daily) frequencies. Third, the fact that index options are traded with maturities ranging from 1 month to 3 years, allows us to estimate an entire term structure of risk free interest rates. Fourth, we find that the price discovery for option-implied interest rates compares favorably to price discovery in the treasury market, suggesting that these rates accurately reflect information available to market participants.

One potential concern with our estimates of the time value of money is that frictions distinct from the convenience yield on safe assets could impact our implied interest rates. We document for our benchmark estimates (using S&P500 index options) that observable measures of frictions (such as bid-ask spreads and market efficiency measures) in the option market do not seem related to our estimated rates. Furthermore, we find similar convenience yields using the futures market for precious metals, suggesting that the only frictions of concern must be common across markets.

We use our new data set in three applications, which specifically require us to observe a term structure of high frequency interest rate (and convenience yield) estimates. First, we do an event study of the effects of monetary policy and quantitative easing on both convenience yields and the time value of money. We find that monetary policy and QE have a nontrivial effect on convenience yields, particularly during the depths of the financial crisis. Because quantitative easing is the purchase of long term treasury bonds and agency mortgage-backed securities financed by the issuance of bank reserves, which are a form of overnight debt, it is unclear whether the effects of quantitative easing spill over beyond the prices of debt securities that are actually purchased. Under the "narrow" view of QE's transmission mechanism, quantitative easing should not spill over broadly into the discount rates at which the private sector can borrow despite the lowering of long-term treasury yields (the asset that is bought).

A "broad" view of the transmission mechanism of quantitative easing on the other hand is common in much of the theoretical literature (Caballero and Farhi (2018)) and Diamond (2018)) which emphasizes that swapping reserves for risky or long duration assets increases the overall supply of safe assets and should therefore reduce convenience yields across markets. Because our interest rates are inferred from assets distinct from the fixed income market, we can use our data to test whether there is a "narrow" or "broad" transmission mechanism and find support for the latter. In fact, we find that our risk free rates are more sensitive to quantitative easing than the associated treasury yields, implying that quantitative easing reduces the scarcity of safe assets as implied by the theoretical literature.

Our second application is on bond return predictability. Because government bond yield movements are affected by the dynamics of convenience yields, a natural question that arises is whether the documented bond return predictability in the literature is related to the dynamics of the convenience yield or to movements in convenience-yield-free rates. We find that a forecasting factor constructed solely from the cross-section of convenience yields in the spirit of Cochrane and Piazzesi (2005) has substantial forecasting power for both government bond excess returns as well as convenience-yield-free excess returns even when controlling for factors in the literature. In univariate regressions, we even outperform the predictive power of conventional predictors in the literature in our sample. The results therefore suggest that a full explanation of the predictability in bond excess returns requires a model that features both a time varying premium related to safe assets (convenience yield) as well as another sources of excess return predictability (i.e. time-varying risk aversion or time-varying volatility).

Our third application studies whether measures of the time value of money denominated in difference currencies are consistent with no arbitrage. The so-called covered interest parity relationship implies that risk free interest rates in different currencies are related to the ratio of spot to future exchange rates between the currencies. Existing measures of violations of covered interest parity (CIP) use interest rates that feature convenience yields (such as government bond rates) or credit risk (such as LIBOR) which raises the question to what extent such violations persist once convenience-yield-free risk free interest rates are used. Using data from Japan and Europe we construct an index option implied interest rate for those two regions as well, and find that by using option-implied rates for both countries, previously documented covered interest parity violations are substantially reduced.

Our paper contributes to several related literatures. First, it contributes to the empirical literature mentioned above on safe assets by providing a measure of the convenience yield that is motivated by and connected to theory. Some existing proxies for the convenience yield are spreads between yields on two different safe assets, which may be an underestimate if both assets have positive convenience yields. Other proxies in the literature are spreads between a safe asset and a low-risk asset, which may be an overestimate if there is a nontrivial credit risk premium on the risky asset. Our computed spreads are larger than spreads in the first category and smaller than those in the second category, which is consistent with the hypothesis that we are obtaining cleaner estimates of the convenience yield on safe assets. We also find that our spread is almost identical to the LIBOR-treasury spread before the crisis but substantially smaller after. This is consistent with the view that credit risk in LIBOR was considered negligible before the crisis but significant afterwards. Similarly, we estimate a somewhat smaller convenience yield than the 73 basis points reported in the seminal paper of Krishnamurthy and Vissing-Jorgensen (2012) using a AAA-treasury spread, perhaps because of some credit risk in AAA bonds. We also contribute to this literature by providing an entire term structure of convenience yields at a minute-level frequency.

Second, we use these unique features of the data to contribute to the literature on monetary policy and quantitative easing event studies. The baseline event study on quantitative easing (Krishnamurthy and Vissing-Jorgensen (2011)) presents spreads between different yields on safe assets but is constrained to a 2 day event window by slow price discovery, while we are able to use estimates within an hour of all event time stamps. No existing work studies risk free rates inferred from assets outside the fixed income market, so our data is ideal for testing how broadly quantitative easing spills over to distant asset classes. In addition, existing high frequency event studies on conventional monetary policy have not examined the response of convenience yields, perhaps due to similar data limitations that we overcome.

Our work also relates to the literature on intermediary asset pricing, particularly the subset of the literature relating arbitrage spreads to financial frictions. He and Krishnamurthy (2013) presents a canonical intermediary asset pricing model, showing theoretically and quantitatively under what assumptions the capitalization of financial intermediaries is a key state variable for the dynamics of asset prices. A related theoretical and empirical paper by Frazzini and Pedersen (2014) presents a model in which the spread between the return on a zero-beta security and the risk-free rate measures the tightness of leverage constraints for levered investors and shows that this zero-beta rate is very high in a large range of asset classes. Measuring a zero-beta rate requires taking a stance on the specific risk factor that the beta is computed against. If the factor does not capture all risks relevant to investors, the zero beta rate includes a risk premium component. In contrast, the risk-free rate we estimate from options markets does not require specifying any particular risk model and implies a considerably smaller spread than the spread estimates in their paper. The spread we estimate therefore measures the tightness of leverage constraints in any multi-factor generalization of their model. Also related to our work is Hébert (2018), who presents a theoretical model in which arbitrage spreads are due to constraints on the trading of financial intermediaries.

The last part of our paper relates to several existing papers (Amihud and Mendelson (1991), Krishnamurthy (2002), Musto, Nini, and Schwarz (2018), Daves and Ehrhardt (1993)) that study individual arbitrages that we consider in our analysis across multiple asset classes. While these papers cannot make statements about the relative size and speed of convergence of different arbitrage related spreads, they do provide additional institutional details about the frictions related to each arbitrage opportunity. The first such paper, Amihud and Mendelson (1991) documents a spread between maturity matched treasury notes and bills and relates it to measures of relative illiquidity. Krishnamurthy (2002) shows that spreads between repo rates makes it difficult for a levered investor to profit from the spread between on and off the run bonds. Musto et al. (2018) shows how the relative liquidity (measured using bid ask spreads and other proxies from the microstructure literature) of notes and bonds contributes to the spread between their yields. Daves and Ehrhardt (1993) shows that the spread between interest and principal STRIPS seems related to measures of their degree of illiquidity. Pasquariello (2014) constructs an aggregate index of multiple arbitrage spreads with the purpose of forecasting risky asset returns. Finally, Golez, Jackwerth, and Slavutskaya (2018) use a combination of 3-month option and futures data on the S&P500 index to construct a daily funding illiquidity measure and find that this measure significantly affects the returns of leveraged managed portfolios by hedge funds.

The paper proceeds as follows. In Section 2, we show how we use the put-call parity relationship on European options to estimate risk free rates. In Section 3 we explore the effects of monetary policy announcements on our estimated rates and compare them to the effects on government bonds and convenience yields (the difference). In Section 4 we explore to what extent the dynamics of the term structure of the convenience yield adds to bond return predictability. In Section 5 we explore CIP deviations using option-implied interest rates across markets. We perform several robustness analyses in Section 6. In Secton 7 we compute commonly used bond spreads from the literature. In Section 8 we then perform a multivariate analysis of these spreads and our various convenience yield measures. Section 9 concludes.

2. Risk Free Interest Rates without Convenience Yields

In this section we propose a novel estimator of a term structure of convenience yield free interest rates using risky assets. The risky assets that we focus on are European-style options on the S&P500 traded on the Chicago Board Options Exchange (CBOE).

2.1. Constructing Risk Free Assets

The starting point of our analysis is the put-call parity relationship for European options. At each time t, for each time to maturity T, option price quotes are available for a large cross-section of different strike prices indexed by $i = 1, ...N$. The put-call parity relationship then states that at time t, for each time to maturity T, and each strike price K_i, the difference between the put price $p_{i,t,T}$ and call price $c_{i,t,T}$ equals the discounted value of the strike K_i minus the current value of the underlying S_t, where we need to adjust the latter for the present value of the cash flow (or convenience) that the security delivers.[3] Denote this present value of the cash flow (or convenience) by $\mathcal{P}_{t,T}$, then the put-call parity relationship is given by:

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

This relationship provides two ways of obtaining the risk free interest rate $r_{t,T}$ implied by these markets.

Estimator 1: At each time t and for each maturity T, we run the following cross-sectional regression:

$$p_i - c_i = \alpha + \beta K_i + \varepsilon_i \tag{2}$$

where the slope of the line is equal to:

$$\beta = \exp(-r_{t,T}T), \tag{3}$$

and where the intercept is equal to:

$$\alpha = \mathcal{P}_{t,T} - S_t. \tag{4}$$

The continuously compounded risk free interest rate at time t for maturity T therefore equals:

$$r_{t,T} = -\frac{1}{T}\ln(\beta). \tag{5}$$

The estimated β of this regression can also be interpreted as the realized risk free return that is earned on a particular trading strategy. To see this, consider the Ordinary Least Squares (OLS) estimator of the slope:

$$\beta_{OLS} = \frac{\sum_i \left((p_i - c_i - \overline{p-c})(K_i - \overline{K})\right)}{\sum_i (K_i - \overline{K})^2} \tag{6}$$

where

$$\overline{p-c} = \frac{\sum_i (p_i - c_i)}{N} \tag{7}$$

[3]For dividend paying stock indices this price is the present value of the dividends paid out between time t and T, also called the dividend strip price (van Binsbergen, Brandt, and Koijen (2012).

and

$$\overline{K} = \frac{\sum_i K_i}{N} \tag{8}$$

So the strategy (also sometimes called the "Box" trade) involves buying (writing) a total of $K_i - \bar{K}$ put options for which the strike is above (below) average and writing (buying) a total of $K_i - \bar{K}$ calls for which the strike is above (below) average for each $i \in 1, ..., N$. This strategy will deliver the continuously compounded realized risk-free rate equal to $-\frac{1}{T}\ln(\beta_{OLS})$.

Estimator 2: At each time t and for each maturity T take all possible combinations of strikes, indexed by $1, ..., A$ where $A = \frac{N(N-1)}{2}$ and compute an implied risk-free rate for that strike pair. That is, $\forall i \in i = 1, ..., N$ and $\forall j \in i = 1, ..., -i, ..., N$ for which $K_i > K_j$, we compute:

$$r_{t,T,a} = -\frac{1}{T}\ln\left(\frac{(p_{i,t,T} - c_{i,t,T}) - (p_{j,t,T} - c_{j,t,T})}{K_i - K_j}\right), \tag{9}$$

with $a \in 1, ..., A$. We then compute the estimate for the risk free as the median over all these implied rates:

$$r_{t,T} = \text{median}_{a \in A}\left(r_{t,T,a}\right). \tag{10}$$

This estimator, which is also known as the Theil–Sen estimator allows for robust estimation of the slope of the regression line even when there are large outliers in the underlying data. It also corresponds to a trading strategy, which is to invest in the strike pair i and j that deliver the median risk-free rate observation. That is, buying the put of strike K_i and the call of strike K_j while writing the call of strike K_i and the put of strike K_j. If one holds these positions till maturity, then the payoff is risk free and equal to $K_i - K_j > 0$. Because buying and writing these puts and calls costs a total of $(p_{i,t,T} - c_{i,t,T}) - (p_{j,t,T} - c_{j,t,T})$, this trading strategy earns exactly the risk-free rate corresponding to the Theil-Sen estimator.

2.2. Data

Our options data contains all option trades and quotes from the Chicago Board Options Exchange (CBOE) on two underlying assets: the S&P 500 index (SPX) and the Dow Jones Index (DJX), between 2004 and 2018. The traded options on these underlying assets are European, implying that the put-call parity relationship should hold exactly (for American options it only holds with an inequality). The data set contains the bid price, the ask price, the strike and the maturity date for a large range of strike prices for each minute. We compute risk-free rate estimates at the minute level using the mid prices using all strike prices for puts and call with a particular maturity. To compute daily estimates, we then take a median over the minute-level estimates in the day.

2.3. Results: Estimated Interest Rates

We now describe the results. We estimate our benchmark rate using S&P 500 (SPX) index options, which gives us extremely precisely estimated interest rates. We study risk free rates implied by the Dow Jones (DJX) options for robustness in Section 6. In Table 1 we provide summary statistics for SPX implied yields for three maturities: 6 months, 12 months and 18 months, and we compare them with the corresponding yields on government bonds as implied by the Nelson Siegel Svensson (NSS) parameters estimated by Gürkaynak, Sack, and Wright, the continuously compounded LIBOR rates, and the fixed rate of an interest rate swap contract written on the Federal funds rate (OIS).[4] [5]

The table shows that for all maturities the average yields on the SPX implied interest rates are above those of the corresponding government bonds and interest rate swaps, and below those of the LIBOR rate. The average difference between the SPX implied rate and the government bond rate (i.e., the convenience yield), is 35-37 basis points per year, with very little variation across maturities. The average difference between the SPX implied rate and the interest-rate swap fixed rate is also 35-37 basis points, and also essentially constant across maturities. The average difference between the LIBOR rate and the SPX implied rate is positive for both the 6-month and 12-month maturities, equal to 7 basis points and 24 basis points respectively. For the 18-month maturity, a LIBOR rate is not available. Furthermore, the LIBOR rate has the lowest volatility, and the interest-rate swap fixed rate

[4] For a description of the NSS procedure see Section 7.2.

[5] There are two ways to compute SPX implied yields for fixed maturities. For simplicity, we linearly interpolate the two closest SPX implied yields around each fixed maturity. Alternatively, we could fit a NSS yield curve. However, our shortest maturity yields are less precisely estimated, because a small amount of price mismeasurement implies a large error in yield esimates due to the scaling by maturity in the calculation of yields. Elsewhere in the paper, we handle this problem by dropping maturities less than 30 days and weighting our loss function by the inverse of duration.

Table 1
Summary Statistics of SPX Option Implied Interest Rates 2004-2018

Zero Coupon Yields: 6 month maturity			
	Mean	St. Dev.	AR(1) (daily)
Option Implied SPX	0.0178	0.0174	0.9995
LIBOR Implied	0.0185	0.0173	0.9999
Government Bond	0.0142	0.0167	0.9998
OIS	0.0143	0.0178	0.9999
LIBOR Implied - Option Implied SPX	0.0007	0.0021	0.9638
Option Implied SPX - Government Bond	0.0035	0.0022	0.9607
Option Implied SPX - OIS	0.0035	0.0023	0.9709

Zero Coupon Yields: 12 month maturity			
	Mean	St. Dev.	AR(1) (daily)
Option Implied SPX	0.0185	0.0171	0.9980
LIBOR Implied	0.0210	0.0160	0.9998
Government Bond	0.0148	0.0164	0.9997
OIS	0.0148	0.0177	0.9998
LIBOR Implied - Option Implied SPX	0.0024	0.0026	0.9148
Option Implied SPX - Government Bond	0.0037	0.0021	0.8738
Option Implied SPX - OIS	0.0036	0.0020	0.9696

Zero Coupon Yields: 18 month maturity			
	Mean	St. Dev.	AR(1) (daily)
Option Implied SPX	0.0194	0.0167	0.9996
Government Bond	0.0157	0.0159	0.9996
Option Implied SPX - Government Bond	0.0037	0.0021	0.9774
Option Implied SPX - OIS	0.0037	0.0017	0.9763

the highest. The autocorrelation of the spreads are all high and typically above 0.9.

To better understand the variation and comovement in the rates, we plot in Figures I, II and III the four interest rates for all three maturities. The three graphs show a consistent pattern. Before 2008 the SPX implied yields are above the corresponding government bond yield, and closely follow LIBOR. Between 2008 and 2017 a substantial deviation from LIBOR occurs and the SPX implied yields are in between the LIBOR rate and the government bond yield. This suggests that between 2008 and 2017 banks faced substantial credit risk, as measured by the spread between LIBOR and the SPX implied zero coupon yield.

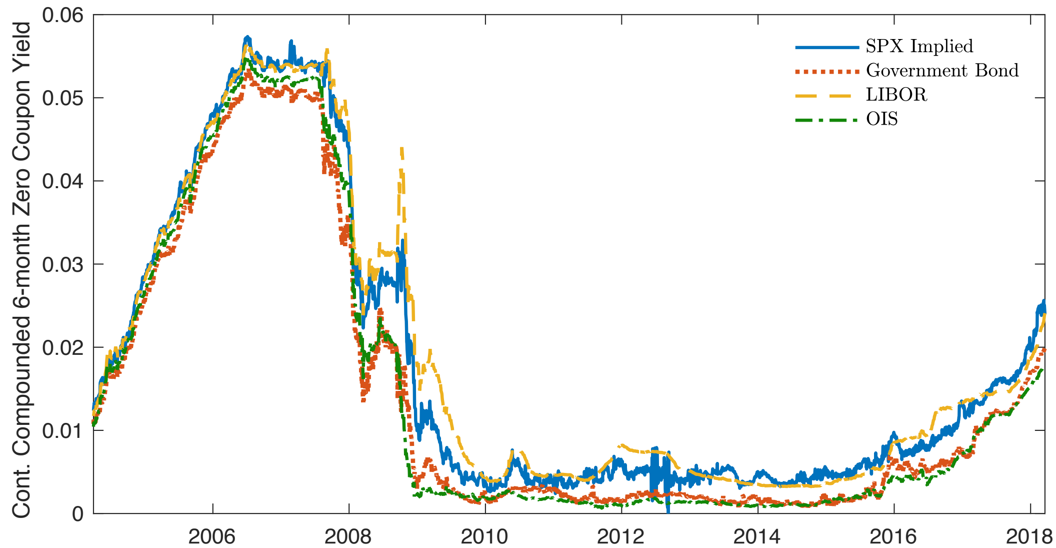


FIGURE I

Comparison of 6-month zero coupon interest rates implied from SPX options with government bond, LIBOR, and OIS rates. All rates are continuously compounded.

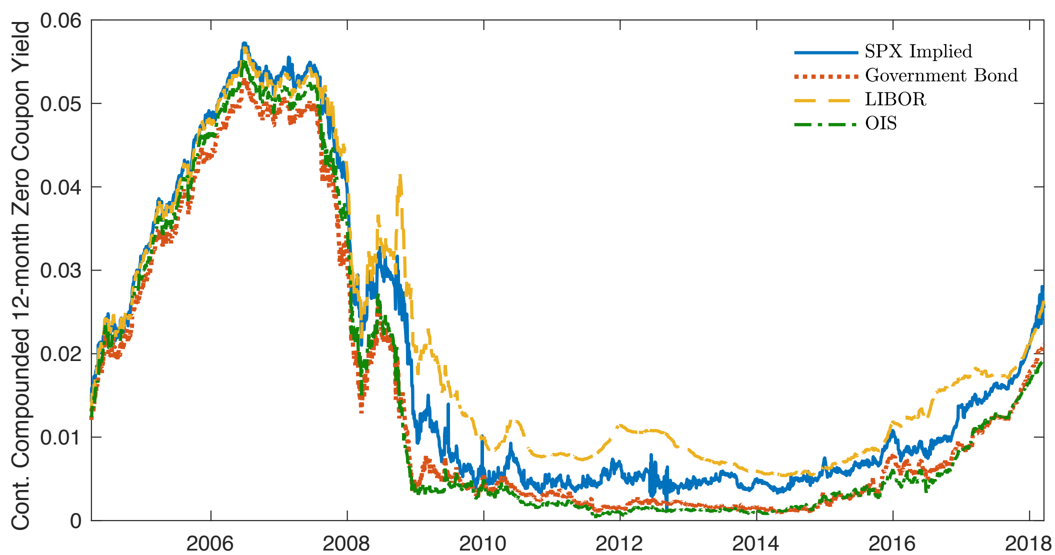


FIGURE II

Comparison of 12-month zero coupon interest rates implied from SPX options with government bond, LIBOR, and OIS rates. All rates are continuously compounded.

Next, we present in Figures IV and V a time series average of daily Nelson-Svensson-Siegel

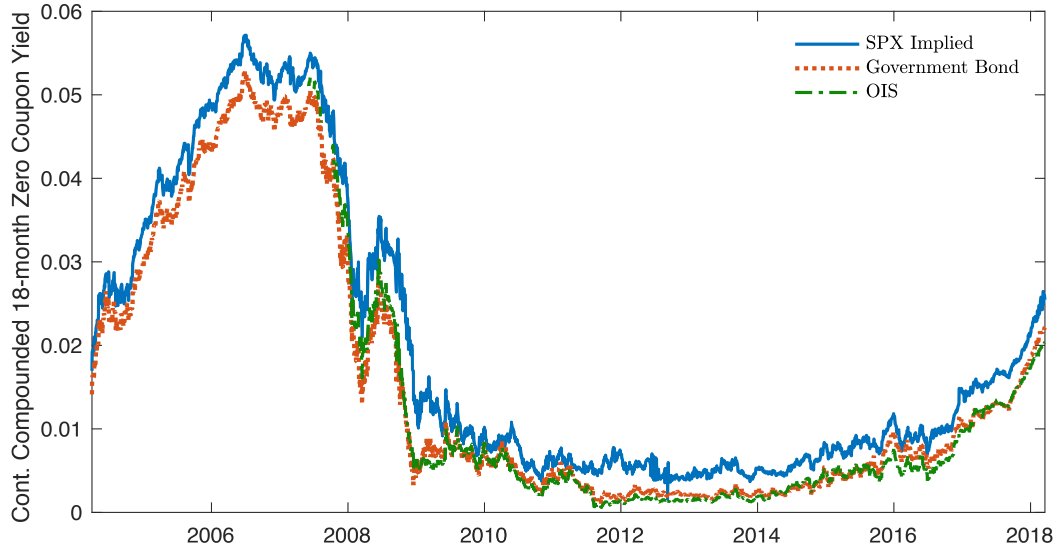


FIGURE III
Comparison of 18-month zero coupon interest rates implied from SPX options with government bond rates and OIS rates. All rates are continuously compounded.

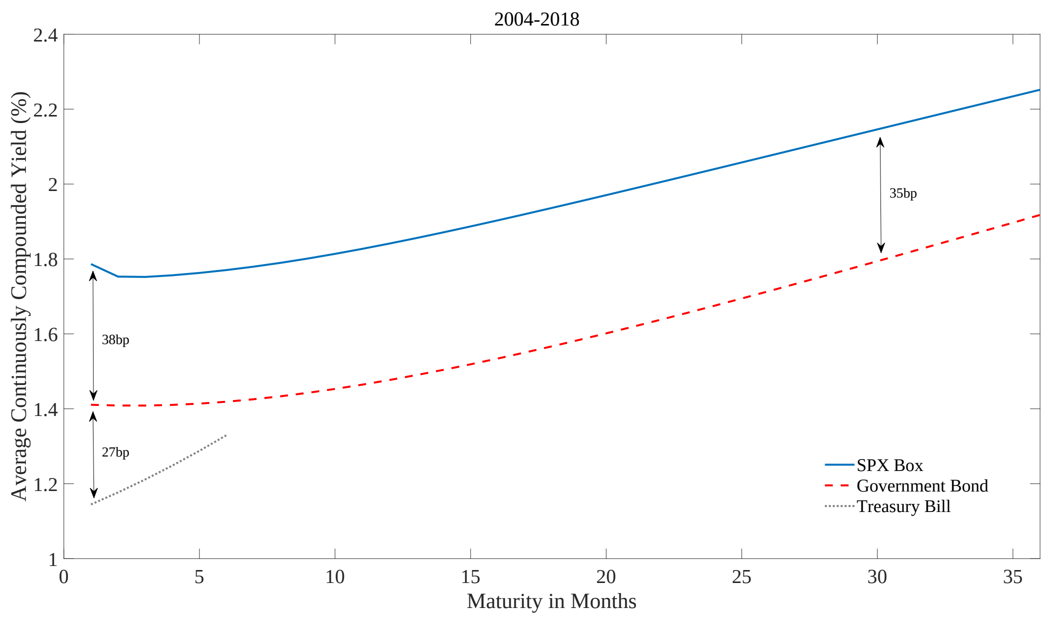


FIGURE IV
Average NSS yields curves fit to SPX box rates and treasury bond rates together with treasury bill rates, 2004-2018. All rates are continuously compounded

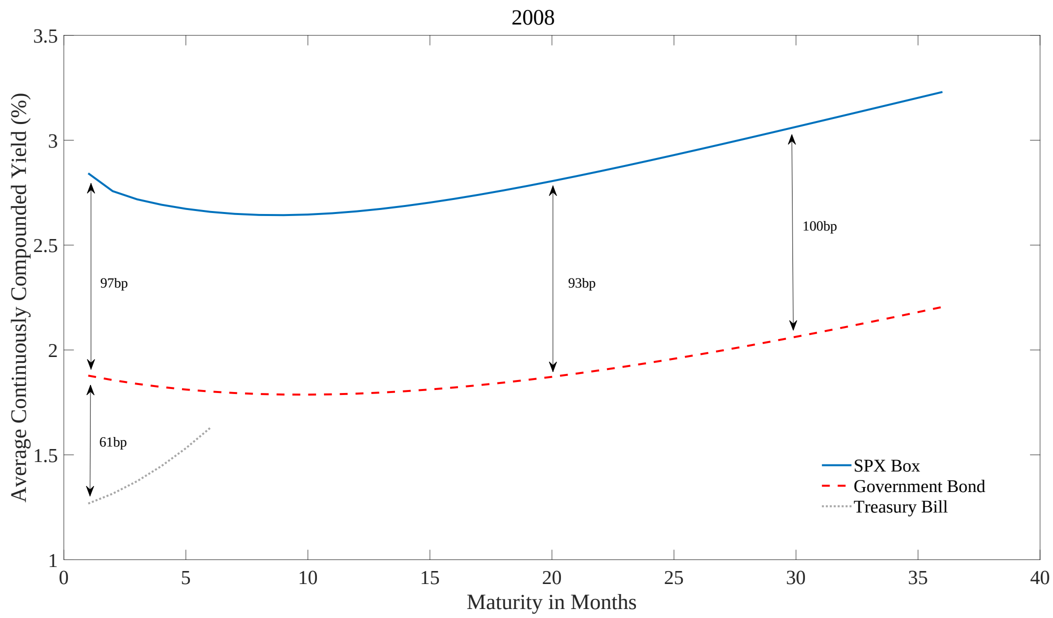


FIGURE V

Average NSS yields curves fit to SPX box rates and treasury bond rates together with treasury bill rates, 2008. All rates are continuously compounded

(NSS) yield curves fit to our SPX implied rates and compare it to the benchmark treasury yield curve of Gürkaynak et al. (2007) for both the full sample, as well as the year 2008. We add to these pictures a curve that is fit to constant maturity treasury bill rates. The average spread between our yield curve and the treasury curve is remarkably flat. The treasury yield curve that is fit to long maturity notes and bonds implies higher short term yields than bills themselves. This spread between actual T-bill yields and the short-term yields implied from the curve that is fit to long-term notes and bonds identifies the additional convenience yield on treasury bills compared to notes and bonds. This additional convenience yields equals roughly 25 basis points. This is consistent with the idea common in the banking literature that short term safe assets are somehow special, and financial institutions therefore have an incentive to finance themselves with large amounts of short term safe debt to exploit the additional convenience yield it earns. Further, our entire term structure of convenience yields shifts outward but remains relatively flat if we restrict our data to only 2008, when the financial crisis was severe. This suggests that the scarcity of safe assets which occurred during the financial crisis was not restricted only to short term debt, and investors were willing to pay a large premium for the safety of even 2.5 year treasury bonds. Our data does not allow us to compute convenience yields beyond this maturity without extrapolating, so it is an open question whether the convenience yields on 10 or 30 year bonds behave similarly.

To further study the differences between the various available interest rates, we plot in Figures VI, VII and VIII the spreads between the SPX implied yield and the government bond yield, as well as the spread between LIBOR and the SPX implied yield with maturities of 6 months, 12 months and 18 months. As LIBOR rates only have maturities up to 12 months, we only plot the spread between the SPX implied yield and the government bond yield for that maturity.

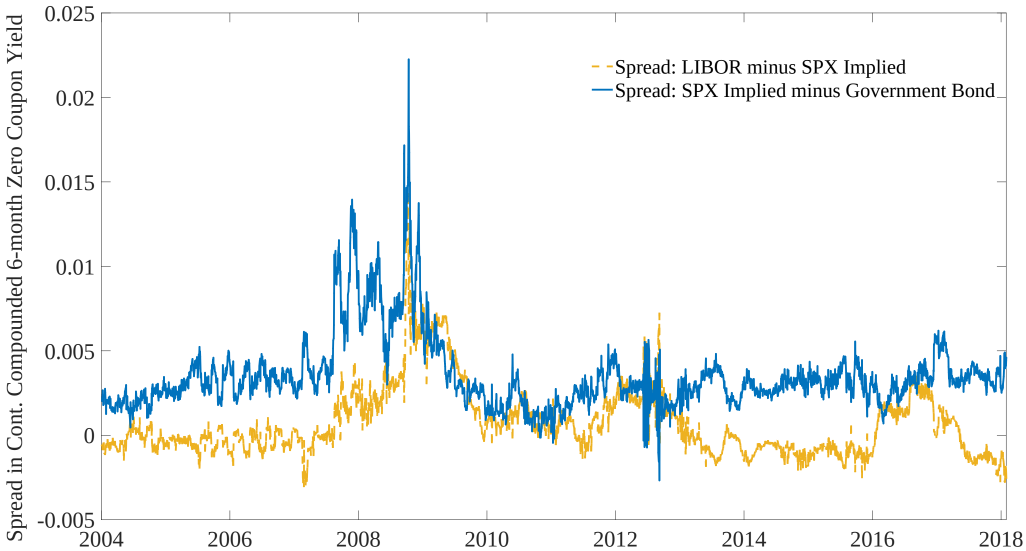


FIGURE VI

Spreads of 6-month zero coupon interest rates implied from SPX options with government bond rates (the convenience yield) and LIBOR rates. All rates are continuously compounded.

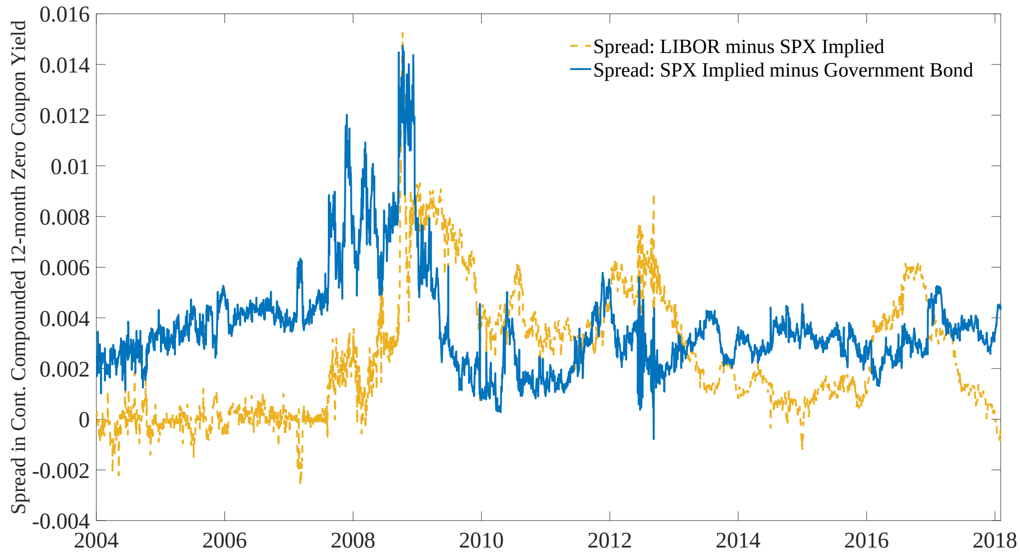


FIGURE VII

Spreads of 12-month zero coupon interest rates implied from SPX options with government bond rates (the convenience yield) and LIBOR rates. All rates are continuously compounded.

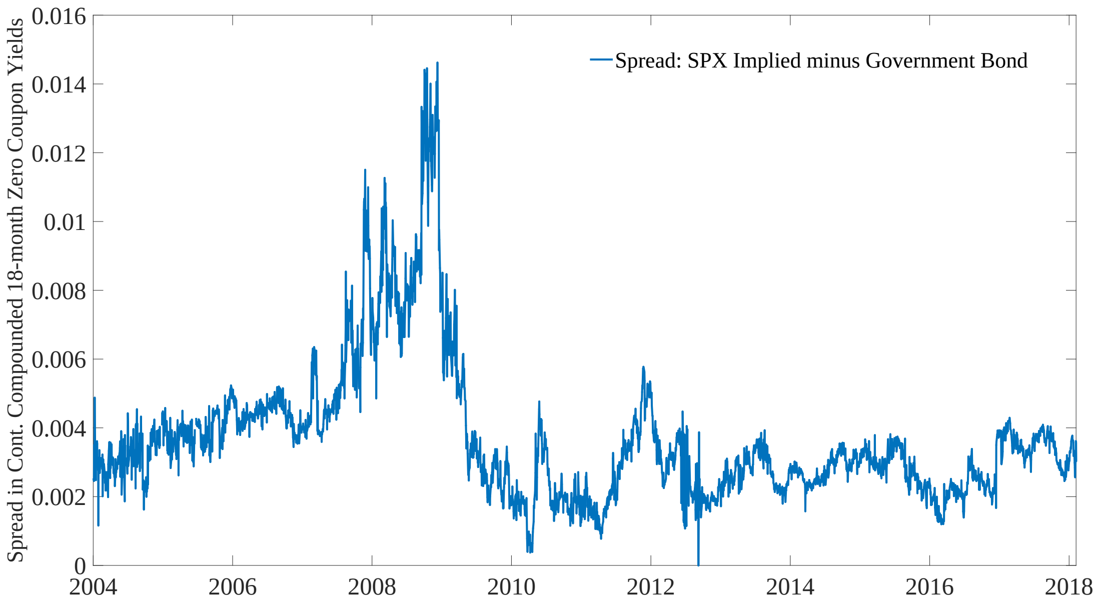


FIGURE VIII

Spreads of 18-month zero coupon interest rates implied from SPX options with government bond rates (the convenience yield) and LIBOR rates. All rates are continuously compounded.

Note that for all three maturities, both spreads exhibit large variation, and they both go up during the crisis and have since been reduced to levels closer to zero.

2.4. Results: Precision of Estimated Rates

In this subsection we evaluate the precision with which our rates are estimated. If no-arbitrage conditions hold perfectly, the R-squared of the regression in equation 2 equals 1 and there is no estimation error in our rates. As such, the R-squared of the regression can be interpreted as a measure of efficiency within the market for options for this particular underlying asset. Because the slope of the regression is so close to 1, we can also easily map this measure of market efficiency to variation in estimated (non-annualized) rates ($Tr_{t,T}$) across the strikes. To see this, note that the population R-squared of the regression in equation 2 is given by:

$$\begin{aligned} R^2 &= \frac{\text{var}(\beta K)}{\text{var}(\beta K) + \text{var}(\varepsilon)} && (11) \\ &= \frac{\beta^2 \text{var}(K)}{\beta^2 \text{var}(K) + \text{var}(\varepsilon)} && (12) \\ &= \frac{1}{1 + \frac{\text{var}(\varepsilon)}{\beta^2 \text{var}(K)}} && (13) \\ & && (14) \end{aligned}$$

Rewriting this equation, we find:

$$\frac{1}{R^2} - 1 = \frac{\text{var}(\varepsilon)}{\beta^2 \text{var}(K_i)} \approx \frac{\text{var}(\varepsilon)}{\text{var}(K_i)}. \quad (15)$$

Assuming uncorrelated error terms, the asymptotic variance of the univariate OLS estimator equals the variance of the error term scaled by N times the variance of the right-hand side variable, that is, the variance across the strike prices. This then implies that the variance of the OLS estimated interest rates can be approximated by (using the approximation that β

is close to 1 and that the log-linearized regression coefficient uncovers the interest rate):

$$\sigma(\hat{r}_{t,T}) \equiv \sigma\left(\frac{1}{T}\ln(\beta_{OLS})\right) \approx \sqrt{\frac{1}{NT^2}(\frac{1}{R^2}-1)} \tag{16}$$

As a consequence, for a regression for maturity $T = 1$, with $N = 20$ strike prices and an R-squared of 0.999999, the standard error of the estimate at each time t (i.e. each minute) is in the order of magnitude of 2 basis points. For 100 strikes, this number is 1 basis point. Given that our daily estimates are computed by taking a median over the minutely observations, the standard error of the daily estimate is even smaller than that. As an illustration, we plot in Figure IX a daily series of the standard error of the minute-level risk free zero coupon yield estimate for the 18 month maturity. We use the actual standard error implied by the regression, which is approximately equal to the non-linear transform of the R-squared as explained in 16, and as such can be interpreted as a measure of market efficiency. To arrive at a daily series for this minute level standard deviation, we take the median standard error across all minutes within a day. The graph shows that the typical standard error is in the order of magnitude of 1 basis point, but it can occasionally spike. The maximum over our sample period is 8 basis points.

3. Convenience Yields, Monetary Policy and Quantitative Easing

We use our data to perform high-frequency event studies of the effects of monetary policy and quantitative easing on the term structure of convenience yields. Our minute-level term structure of convenience yields is ideal for this purpose and broadens the set of questions that can be examined using high frequency event studies. Existing event studies on the effects of quantitative easing (Krishnamurthy Vissing-Jorgensen (2011)) use two-day event windows because of issues related to slow price discovery. While price discovery in treasury bonds themselves is quite fast, more illiquid bonds such as agency debt, corporate debt, or mortgage-backed securities have posed an issue for high frequency event studies. Because our box rate estimates seem to have price discovery roughly as fast as treasuries (see Section 6),

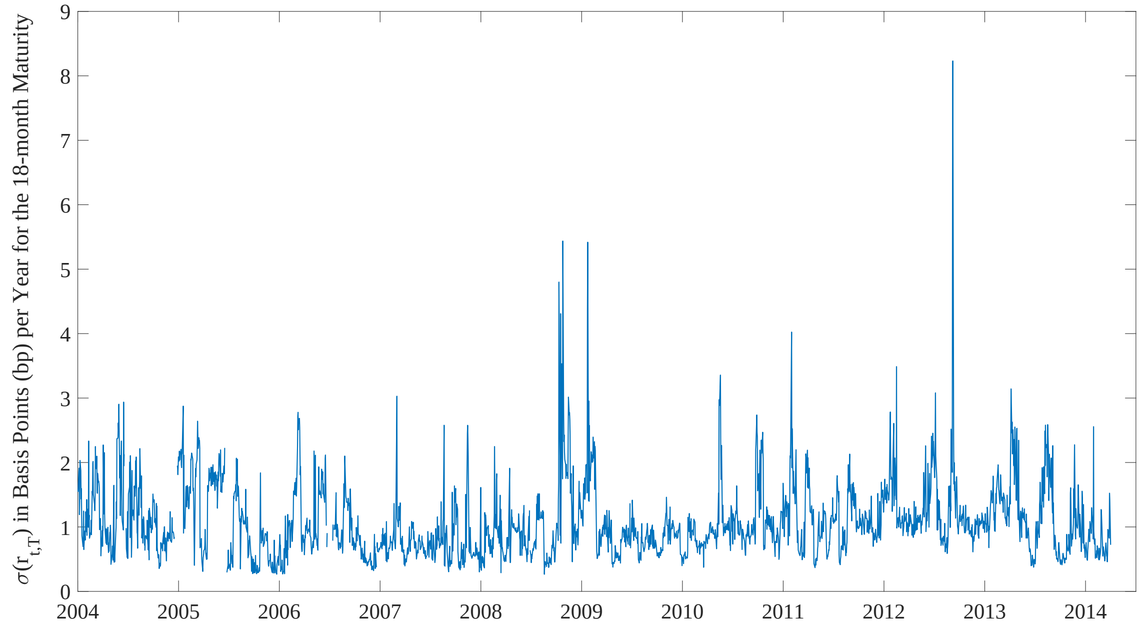


FIGURE IX

Efficiency in the SPX option market expressed as the standard error around the implied risk-free rate.

we are able to measure spreads between different risk free rates using a considerably shorter event window than would otherwise be possible. There is a large literature on the high frequency effects of monetary policy on asset prices (Bernanke and Kuttner (2005), Rigobon and Sack (2004), Nakamura and Steinsson (2018)), but before our paper this literature has not presented results on convenience yields, arguably for similar reasons related to slow price discovery.

If liquidity is an important channel in the monetary transmission mechanism, we should find that monetary stimulus (either conventional and/or unconventional) reduces convenience yields. An idea going back to the LM curve of the IS-LM model (Hicks) that has been justified with recent empirical support (Nagel (2016)) is that the nominal interest rate measures the liquidity premium on assets such as cash and checking accounts (that pay no interest). As a result, an interest rate increase should make liquidity more scarce and increase the convenience yield on safe assets. Because our box rate is inferred from risky assets which should have little to no convenience yield, we are able to decompose the effects of central bank policy on bond yields into changes in the time value of money and changes in convenience yields. Our contribution is to present more direct evidence that monetary stimulus reduces convenience yields. Existing evidence mainly shows that nominal interest rates are correlated with spreads between different rates.

Our results on quantitative easing provide evidence that disciplines our understanding of its transmission mechanism, making progress on the state of knowledge in which Ben Bernanke said it "works in practice but not in theory." Because quantitative easing is the purchase of long term treasury bonds and agency mortgage-backed securities financed by the issuance of bank reserves (which are a form of overnight debt), it is unclear whether what is bought or what is sold in the transaction determines its effects. The seminal paper by Krishnamurthy and Vissing-Jorgensen (2011) presents empirical evidence on the transmission mechanisms of quantitative easing and discusses several possible channels. One view is that reducing the supply of treasuries should make long duration safe assets more scarce and therefore increases their convenience yield. Under this "narrow" view of QE's transmission mechanism, quantitative easing should not spill over broadly into the interest rates at which the private sector can borrow, despite lowering treasury yields. A "broad" view of the transmission mechanism of quantitative easing is common in much of the theoretical literature (Caballero and Farhi (2018) and Diamond (2018)), which emphasizes that swapping reserves for long duration assets increases the overall supply of safe assets and should therefore reduce convenience yields. Because our box rates are inferred from equity option prices, an asset class quite distinct from the fixed income market, our data is ideal for testing whether there is a "narrow" or "broad" transmission mechanism.

3.1. Effects of Quantitative Easing

Our results on the effects of quantitative easing follow a literature which has identified specific dates and times at which policymakers conveyed news about their intention to increase or decrease the size of the program. For the first two rounds of the program, which occurred respectively in 2008/2009 and in 2010, we use the same dates as Krishnamurthy and Vissing-Jorgensen (2011). For Q.E. 3, which happened after the aforementioned paper, we follow the dates in Di Maggio, Kermani, and Palmer (2019). The five event dates for

Q.E. 1 are 11/25/2008/, 12/1/2008, 12/16/2008, 1/28/2009 and 3/18/2009. For Q.E. 2 we consider the event dates 8/10/2010, 9/21/2010, and 11/3/2010. For Q.E. 3 we consider the event dates 9/13/2012, 5/22/2013, 6/19/2013,7/10/2013, and 9/18/2013. For each date we have precise time stamps of the event. To illustrate the quality of our minute-level data, we plot in Figure X the minute-level box rates on March 18th 2009, for three different maturities. The time of the QE announcement was at 2.15pm. The picture clearly shows the effect of the announcement for all three maturities and particularly for the shortest maturity, it seems that rates started moving before the actual announcement.[6]

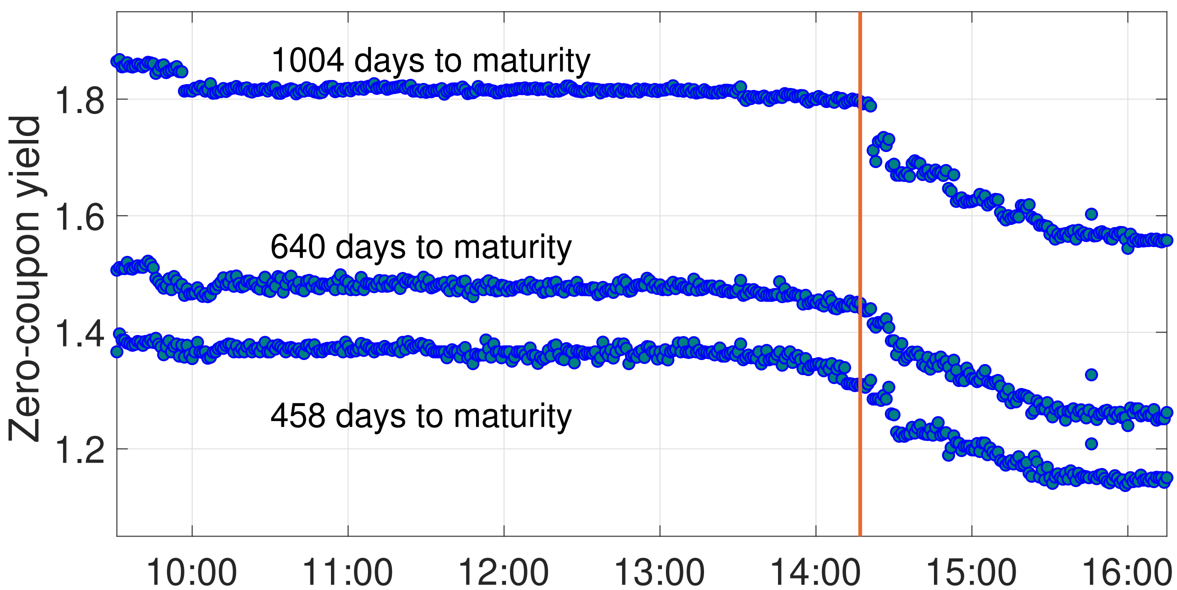


FIGURE X

S&P500 Box Rates on March 18, 2009: The figure plots the minute-level box rates for three different maturities on March 18, 2009. The vertical line represents the time of the release (14:17).

To analyze the effect across all QE dates, we take the median yield on every asset in a window 30 to 60 minutes before the time stamp and 30 to 60 minutes after the time stamp. [7] We then fit Nelson-Siegel-Svensson yield curves to these median yields before and after each event. In particular, we fit one yield curve to our intraday SPX box rates and a second

[6] See also Cieslak, Morse and Vissing-Jorgensen (2019).

[7] This is not possible for 2 of our time stamps, since they occur too early in the day. On 11/25/2008, the time stamp is before the start of trading, so we use the median yield in the last 30 minutes of the previous day and the median yield in the first 30 minutes of the day. On 5/22/2013, we use the median yield between 0 and 30 minutes before the 10am timestamp and 60 to 90 minutes after.

yield curve to intraday indicative quotes on treasury yields from GovPX. For all quotes we use a midpoint of bid and ask.

To summarize our results, we find that both monetary policy and quantitative easing have quite strong effects on convenience yields during the worst of the financial crisis (the second half of 2008 and first half of 2009) but considerably more modest effects otherwise. We report in the figures below the effects of the central bank policies on 3-month, 12-month, and 30-month yields. We report results on treasury yields, box yields, and the convenience yield (which equals their difference). The maturities of 3 and 30 months are the most extreme durations for which we can present results without extrapolating beyond where our data lies.

We find that for Q.E. 1 (i.e., the first round of quantitative easing) which occurred between November 2008 and March 2009, box yields fell considerably more than treasury yields. In Figure XI below, we show that 12 and 30 month box yields fell by 88 and 86 basis points respectively, while treasury yields of the same maturity only fell by 46 and 61 basis points. This results in a reduction in 12- and 30-month convenience yields of 42 and 25 basis points. At the shorter 3 month maturity, government yields fell by only 2 basis points while box yields fell by 37 basis points leading to a 36 basis point reduction in the convenience yield. The lack of response in short term government rates is likely due to the fact that those rates were already at the zero lower bound, while all box rates were considerably higher than treasury yields at this time. The greater drop in box than treasury yields provides evidence in favor of a broad transmission of quantitative easing, in which asset prices outside of narrowly defined fixed income markets also respond. Because risky assets are priced without the convenience yield (that is, consistently with our box rate rather than treasury rates), this implies that quantitative easing reduced the cost of capital for private firms that issue risky securities by even more than is suggested by the drop in treasury yields. It also implies that Q.E. 1 can be thought of as an increase in the supply of safe assets, by swapping more scarce reserves for less scarce treasuries or agency mortgage-backed securities. This relative scarcity is consistent with our finding that the convenience yield is largest at the shortest maturities.

For Q.E. 2 and 3, we find considerably smaller effects on treasury yields and effects with ambiguous signs on the convenience yield on safe assets as reported in Figure XII. Summing up across all 8 event dates in this period, we find that 3, 12, and 30-month treasury yields

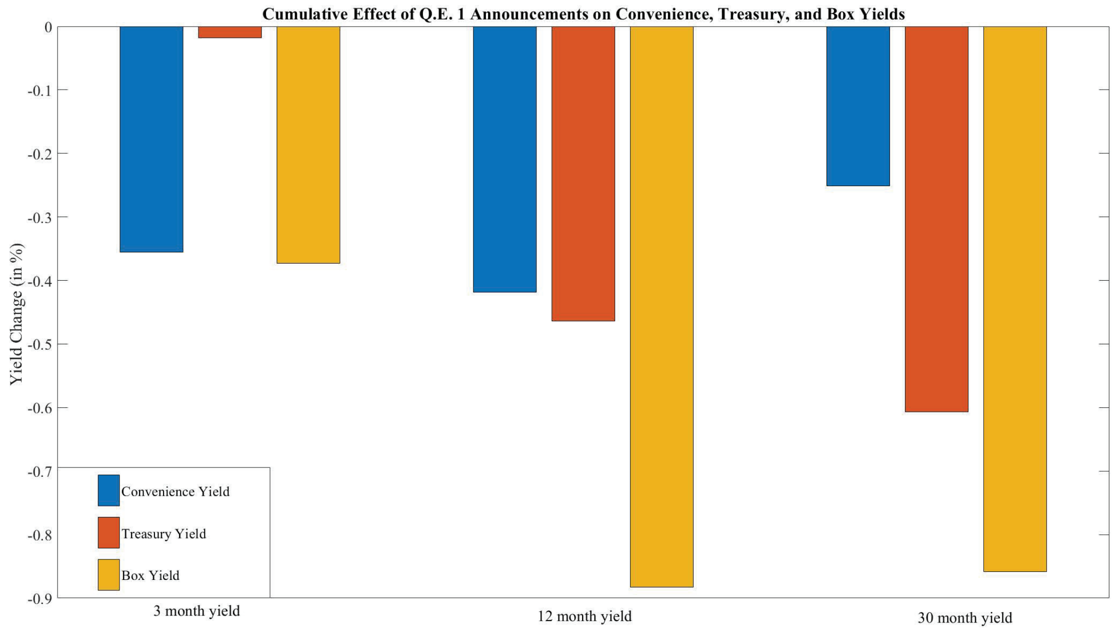


FIGURE XI

Effect of QE 1 on government bond yields, box yields, and convenience yields (i.e. the difference between the two) across various maturities.

fell by 3, 4 and 11 basis points respectively. At the same time, 3, 12 and 30-month box yields fell by 6, increased by 3, and fell by 8 basis points respectively. This lead to a 3 basis point decrease in the 3 month convenience yield and a 7 and 3 basis point increase in the 12 and 30 month convenience yield. The aggregate effect of all Q.E. 2 and 3 announcements is of considerably smaller magnitude than the effect of Q.E. 1. In particular, if anything, it seems to increase the convenience yield on treasuries, though the effect is small and of ambiguous sign across the yield curve.

One possible explanation of our results is that quantitative easing after 2009 was performed outside of the depths of the financial crisis, at which point convenience yields had already converged back to normal levels. It may be that quantitative easing is a weaker policy tool when the financial system is not in distress. Another possible explanation is that the news in this sample on average did not surprise investors as much, with event days including both news that increased and decreased investors' expectations about the size of the program. Regardless of the explanation, it is immediately clear that the large effects found in Q.E. 1 do not seem to generalize to this extension of the program after the depths of the crisis.

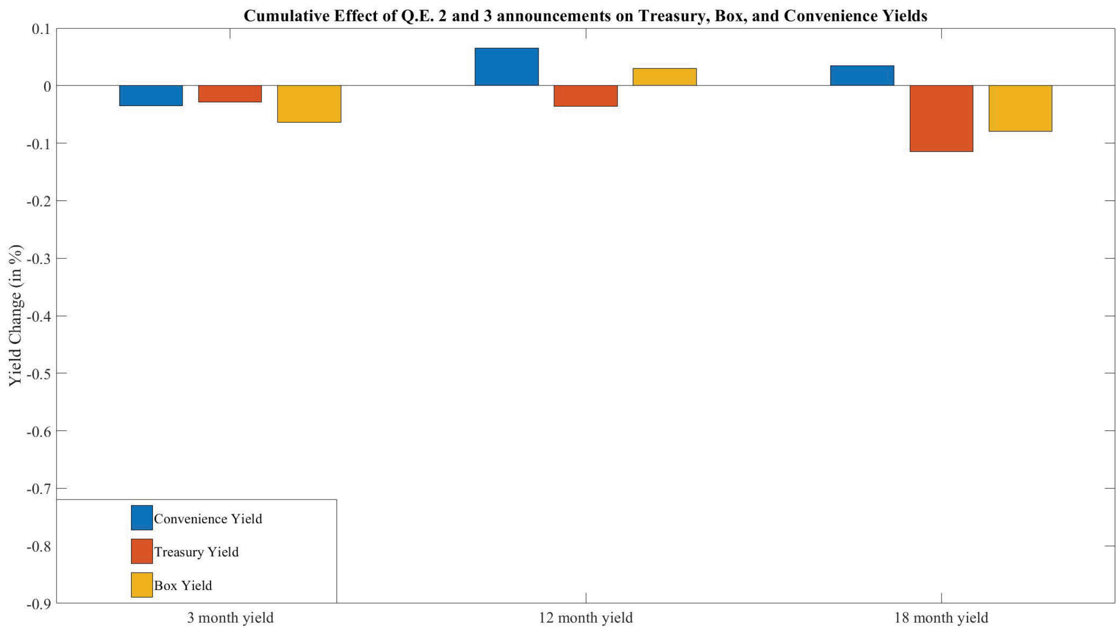


FIGURE XII

Effect of QE 2 and 3 on government bond yields, box yields, and convenience yields (i.e. the difference between the two) across various maturities.

3.2. Monetary Policy Event Studies on FOMC announcement dates

To study the effect of conventional monetary policy on convenience yields, we perform a high frequency event study using all FOMC announcements from 2004 to 2018, the time period in which we have box rate data. We measure unanticipated shocks to monetary policy using innovations in federal funds futures from the Chicago Mercantile Exchange (CME) around each FOMC announcement. Our measure of a monetary policy shock is analogous to that of (Bernanke and Kuttner (2005) and Nakamura and Steinsson (2018)). We use the first trade more than 10 minutes before and the first trade more than 20 minutes after each announcement in order to compute our monetary surprise. Given this monetary policy shock, we fit yield curves to GovPX treasury quotes and our box yields in windows 30 to 60 minutes after each announcement. We then regress the change in each yield around an announcement on our measure of the monetary shock associated to that announcement and use our estimated regression coefficient to predict the effects of a 100 basis point surprise increase in the federal funds rate when reporting our results below.

Similar to our quantitative easing results, we find that monetary policy has considerably stronger effects on convenience yields in the depths of the crisis than at other times. In Figure XII) below we show the results for the whole sample. A 100 basis point rate increase leads to a 54, 88, and 74 basis point increase in box yields for the 3, 12 and 30-month maturities respectively. It leads only to 52, 63, and 45 basis point increases in the 3, 12, and 30-month treasury yields. This results in an increase of the convenience yield of 2, 26, and 28 basis points respectively. This implies that particularly at longer maturities, an increase in the federal funds rate leads to increases in the convenience yield that are more than a third the size in the increase in treasury yields. Similar to quantitative easing, the effect of monetary policy spills over to unrelated asset classes like equity index options.

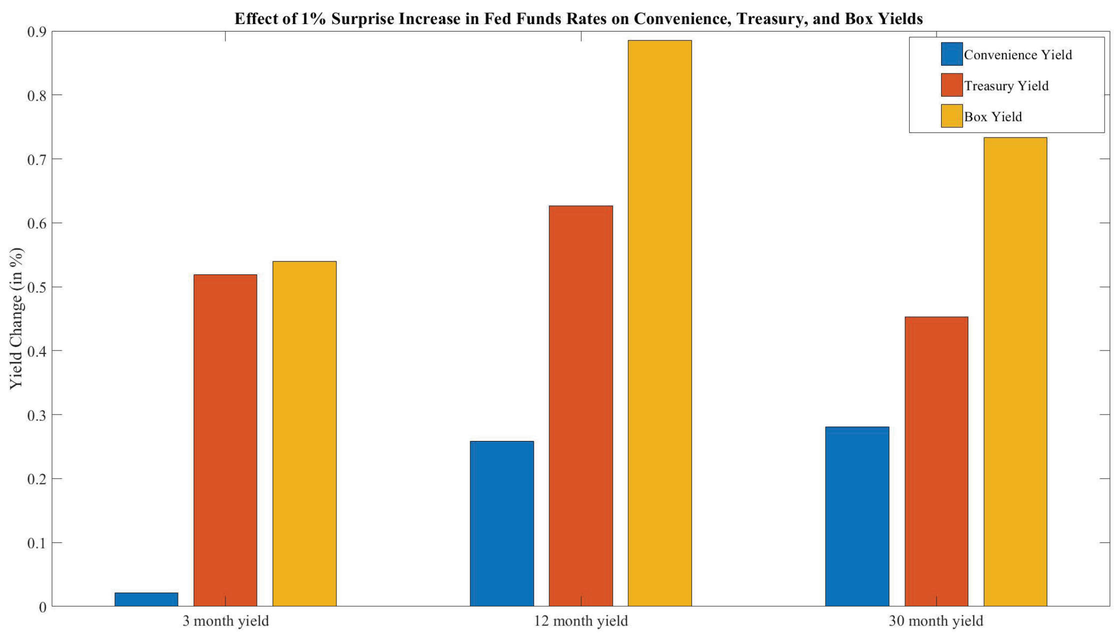


FIGURE XIII

Effect of FOMC Announcements on government bond yields, box yields, and convenience yields (i.e. the difference between the two) across various maturities over the sample 2004-2018.

Next, we present results in Figure XIV from an identical event study but ignoring data from the second half of 2008 and first half of 2009. The results change considerably. Like before, we find that treasury yields respond quite strongly to monetary policy. A 100 basis point increase in the fed funds rate leads to 70, 55, and 34 basis point increases in the 3, 12, and 20 month treasury yields. However, there is only a 32, 66, and 46 basis point increase in the 3, 12, and 20 month box rate. This leads to a 38 basis point decrease in the 3 month convenience yield and a 11 and 13 basis point increase in the 12 and 30 month convenience yields. It therefore seems that by simply removing one year of the worst of the financial crisis from the data, the results imply a considerably weaker (and ambiguously signed) effect of monetary policy on convenience yields. That said, it does seem robustly true that rates in the equity options market move in the same direction as treasury yields and with reasonably large magnitudes, suggesting that monetary policy broadly decreases risk free rates even outside the narrowly defined market for safe, money-like securities.

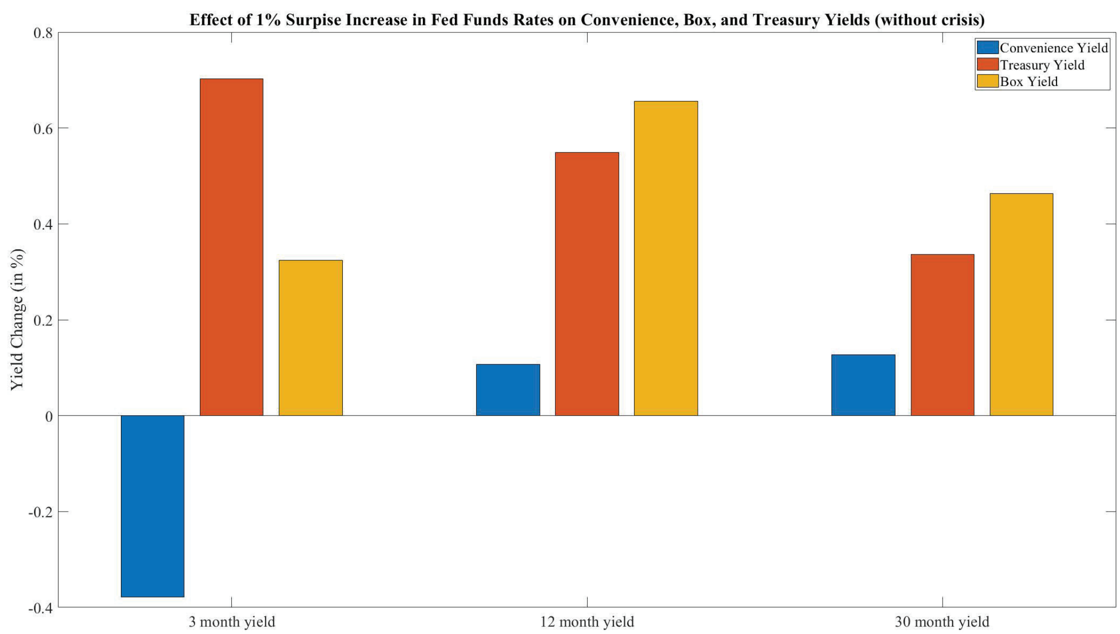


FIGURE XIV

Effect of FOMC Announcements on government bond yields, box yields, and convenience yields (i.e. the difference between the two) across various maturities for the sample 2004-2018 but excluding the crisis period.

4. Bond Return Predictability

A literature as early as Fama and Bliss (1987) has focused on the predictability of government bond returns using information contained in the term structure of bond returns.

This large predictability has been one of the more difficult empirical findings to square with asset pricing theory, particularly given the seeming disconnect of these time varying expected excess returns from the documented variation in expected excess return in stock markets.

Because of our unique term structure of convenience yields, we can decompose government bond returns into movements in the time value of money and convenience yields. In particular, we have defined the convenience yield $cy_{t,n}$ as the difference between the implied (continuously compounded) yield inferred from S&P500 options and the yield on government bonds:

$$cy_{t,n} = y_{t,n}^{box} - y_{t,n}^{gov}, \tag{17}$$

where n is the time until maturity. Rewriting this equation we find:

$$y_{t,n}^{gov} = y_{t,n}^{box} - cy_{t,n}. \tag{18}$$

The excess return on government bonds, which is given by:

$$rx_{t+1,n}^{gov} = ny_{t,n}^{gov} - (n-1)y_{t+1,n-1}^{gov} - y_{t,1}^{gov} \tag{19}$$

can then be written as the difference between two return components, the one related to changes in the box rate and the one related to changes in the convenience yield:

$$rx_{t+1,n}^{gov} = ny_{t,n}^{box} - (n-1)y_{t+1,n-1}^{box} - y_{t,1}^{box} - ncy_{t,n} + (n-1)cy_{t+1,n-1} + cy_{t,1}. \tag{20}$$

This then naturally raises two questions. First, to what extent is the predictability in government bond returns related to each of these two components? Is it driven by predictable variation in excess box returns, or predictable variation related to the convenience yield component of returns? Second, is the predictive power in current yields due to the component due to convenience yields or the component due to the time value of money?

To provide a first answer to these two questions, we use the approach proposed by Cochrane and Piazzesi (2005) and use the cross-section of yields to construct a return forecasting factor. We construct two such factors. The first replicates the one of Cochrane and Piazzesi (2005) for the 2004-2018 sample. For the construction of the second forecasting factor, we follow the exact same procedure (using the same left-hand side variables), but instead of using as the forecasting variables the cross-section of government bond yields, we use the cross-section of convenience yields. We then evaluate the forecasting power of these two factors individually and jointly using excess returns on government bonds and excess returns on box rates focusing on the 2-year maturity only (we do not have longer maturity claims available for the box rate).

The results are summarized in the table below. The results show that the factor constructed from the convenience yield substantially predicts both government bond returns as well as box rate returns. In the joint regression, both the convenience yield factor and the Cochrane Piazzesi factor show up significantly. In traditional asset pricing models where the consumption Euler equation prices all assets, there is no convenience yield and thus no predictability resulting from it. Overall, the results therefore suggest that a complete explanation of bond return predictability requires a model that features both time varying risk aversion (or volatility) as well as a time varying premium related to safe assets (convenience yield).

	$rx^{gov}_{t+1,2}$	$rx^{gov}_{t+1,2}$	$rx^{gov}_{t+1,2}$	$rx^{box}_{t+1,2}$	$rx^{box}_{t+1,2}$	$rx^{box}_{t+1,2}$
β^{CP}	0.299***		0.196***	0.357***		0.204***
β^{CY}		0.415***	0.329***		0.580***	0.489***
Adj. R^2	0.231	0.319	0.403	0.258	0.488	0.560

5. The box-rate-implied CIP deviation

One important no-arbitrage relation that has received increasing attention in recent years, is the so-called *Covered Interest Parity* relationship (CIP). CIP states that the premium of a currency's forward over the spot exchange rate between two countries equals the difference between the nominal interest rates of those two countries. Recently, however, Du, Im, and Schreger (2018a) and Du, Tepper, and Verdelhan (2018b) have shown large, and persistent violations of CIP using government bond and LIBOR yields as the measure for the nominal interest rate. As argued previously, government bond yields feature a convenience yield and LIBOR contains credit risk. As a consequence, it is informative to compute a measure of CIP deviations using our convenience-yield-free risk free interest rates.

Imagine a US-based agent at time t facing two alternative strategies. He can either invest in a riskless asset denominated in dollars with n years to maturity (in our case the U.S. box rate), or exchange money into a foreign currency, invest it into the riskless asset denominated in that currency for n years (the box rate constructed for the foreign country) and buy a promise to exchange the money back into dollars at a predetermined rate at time $t + n$. More formally, denote with $r_{t,n}$ and $r^*_{t,n}$ the continuously-compounded box rates at time t with n-year maturity for the domestic and foreign country. The CIP relation that we are exploring in this section is then given by:

$$e^{nr_{t,n}} = e^{nr^*_{t,n}} \frac{S_t}{F_{t,n}}, \tag{21}$$

where S_t is the time-t spot exchange rate between dollars and foreign currency and $F_{t,n}$ the forward rate of exchange, set at time t with a n-year maturity.

We construct the *cross-currency basis*, in logs, as

$$x_{t,n} = r^*_{t,n} - r_{t,n} - \frac{1}{n}\ln(S_t/F_{t,n}) \tag{22}$$

$\frac{1}{n}\ln(S_t/F_{t,n})$ is the annualized continuously-compounded "forward premium".

We analyzie the CIP deviation between the U.S. dollar and the Japanese yen. The data on futures trades are obtained from the Chicago Mercantile Exchange (CME). Every day, more than \$100 billion are traded over the CME FX markets, which makes the CME the world's largest regulated marketplace for foreign currency trading.[8] Spot exchange-rate quotes are from the TrueFX dataset, which offers historical tick-by-tick market data for dealable interbank foreign exchange rates at the millisecond frequency. For spot exchange rate quotes, we take the mid-point between bid and ask rates. We compute the median spot and the median forward rate every minute, and match the spot and forward rates in the

[8] See https://www.cmegroup.com/trading/fx/why-trade-fx-futures-and-options.html

same minute. We construct the forward premium, and compute the daily median.

To compute the Japanese box rate, we use European options on the Nikkei 225 index provided by the Japan Exchange Group. Each observation corresponds to a quote in response to a new order. We then construct the mid quote at a minute level. To be precise, we consider the best bid and the best ask each minute, and use only those minutes in which both an order to sell and to buy are submitted. Finally, we restrict our attention to those minutes, maturities, and strikes for which the minimum ask price is not larger than 1.5 times the maximum bid price. The rest of the procedure for constructing the box rates from mid quotes follows the one outlined in Section 2. Per each maturity and date, we compute a daily median.

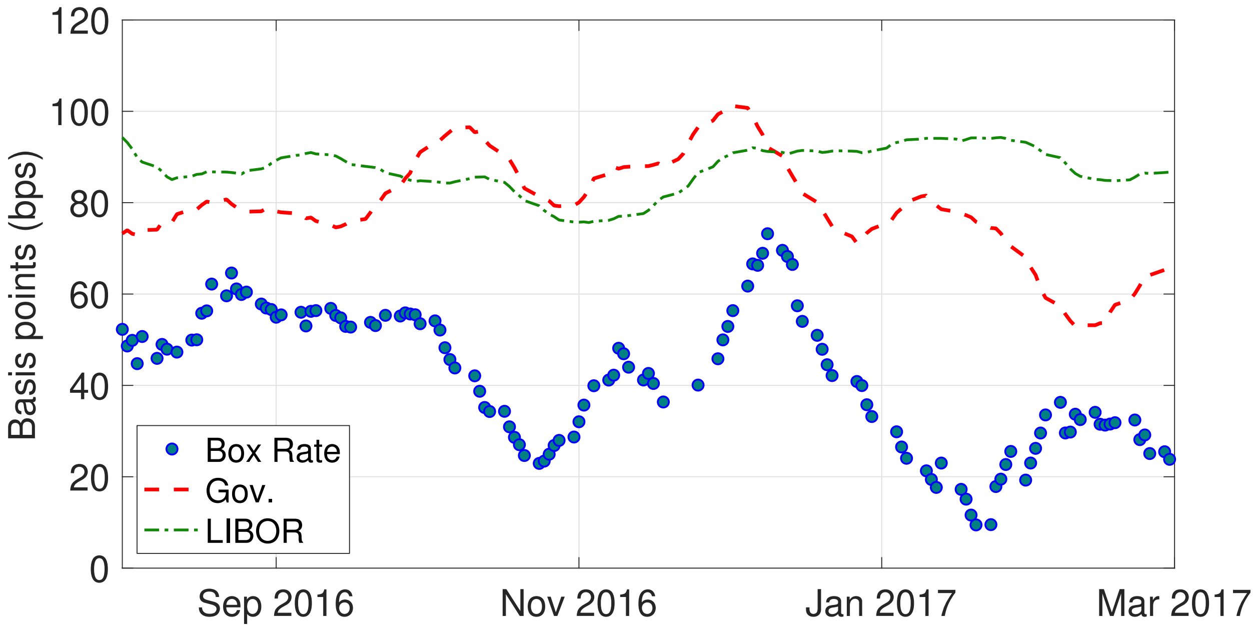
We then linearly interpolate box rates on both currencies to match the maturity of the forward contract. Figure XV depicts the cross-currency basis in bps implied by box rates, and the ones computed by Du et al. (2018a,b). These authors use U.S. and Japanese government bonds and LIBOR respectively to construct their cross-currency bases. To make our results comparable to existing work, we use the forward contract with the maturity closest to 90 days. The average maturity for our series is 97 days. What stands out from the picture is how the box-rate-implied CIP deviation is almost always smaller (closer to zero) than previous estimates. The average value of the cross-currency basis we calculate is 41 bps relative to the 79 bps for the Du et al. (2018a) series in the same period. The difference of 38 bps is driven by two effects: (1) a more precise estimate of the forward premium (daily median of minute-level forward premia instead of end-of-the-day values), and the usage of box rates rather than government bonds. In the same period, the CIP violation computed using LIBOR rates is 87.5 bps.

6. Robustness

In this section we perform several robustness analyses related to our implied interest rates. First, we compare our SPX implied box rates to three other interest rates: the GC repo rate, the DJX option-implied box rate, and the risk free rate implied by precious metal futures. Second, we demonstrate that the size of the bid-ask spreads for options has little to

FIGURE XV

CIP Deviation: Box rate, government bond, and LIBOR



The figure shows a ten-day rolling moving average of the Dollar-Yen cross-currency basis implied by box rates, as those implied by government bonds and LIBOR presented in Du et al. (2018a) and Du et al. (2018b) at a 3 month maturity.

no effect on the level of our estimated rates, suggesting that option microstructure frictions are not a driver of the level of convenience yields nor their variation. Third, and finally, we demonstrate that the speed of price discovery in our box rates favorably compares to that of treasury bonds, validating our choice of picking a narrow event window around monetary policy announcements.

6.1. Relation to Other Interest Rates

In this subsection, we compare our box rate to three other interest rate proxies. First, we show that the average level of the General Collateral (GC) repo rate (which is only available for short maturities) equals that of the government bond yields implied by the NSS curve. As a result, GC repo also seems to earn a convenience yield close to that of government bonds. More importantly, we can confidently conclude that our rate is distinct from other common benchmarks in the literature, including government bond yields, OIS rates, Libor and GC repo rates.

Second, we estimate risk free rates from DJX (Dow Jones) options instead of SPX options. We find that the implied rates and associated convenience yields are highly similar to those implied by the SPX, though the DJX estimated rates are substantially noisier, with lower R-squared values (and associated higher standard errors) in our estimated cross-sectional regressions. This demonstrates that our data on SPX options yields uniquely precise rate estimates and that the nearly perfect fit of the put-call parity relationship is due to the quality of the SPX option market, rather than a mechanical feature of how option quotes are generated.

Third, we use the cost-of-carry formula for previous metal futures to infer implied interest rates from that derivative market. Generally, the time-varying cost of storage of a commodity can complicate the estimation of a risk-free rate from the cost-of-carry formula. We resolve this issue by focusing on previous metals for which the storage cost as a fraction of the value of the underlying asset is minimal. Using this risk free interest rate proxy, we once again find similar convenience yields to those implied by option markets (equal to about 40bp over our sample period).

6.1.1. GC Repo

In this section we study the GC repo rate and compare it to several other interest rates. The GC repo rate is the interest rate earned on a loan collateralized by a safe financial asset such as treasuries, agency securities, or other members of the so-called "General Collateral" basket of safe assets. It is commonly used in the literature Nagel (2016) to measure a riskless rate of return that is higher than that earned by special liquid assets such as Treasury Bills. It is generally available for shorter maturities than the ones we study in this paper.

In Table 2 we compare the summary statistics of our 3-month box rate to those of the 3-month government bond yield (implied by the NSS curve), the 3-month OIS rate and the 3-month GC repo rate. We find that the average rate across government bonds, OIS and GC repo are all very similar, whereas our implied box rate is substantially above all three. We can therefore conclude that our rate is distinct from other common benchmarks in the literature, which all seem to feature some form of convenience yield.

Table 2
Summary Statistics of SPX Option Implied Interest Rates 2004-2018

Zero Coupon Yields: 3 month maturity			
	Mean	St. Dev.	AR(1) (daily)
Option Implied SPX	0.0174	0.0176	0.9997
Government Bond	0.0142	0.0169	0.9997
OIS	0.0139	0.0178	0.9999
GC Repo	0.0154	0.0176	0.9997

6.1.2. Box Rates from the Dow Jones Industrial Index (DJX)

Next, we repeat the box rate estimation that we performed for the S&P 500 index for options on the Dow Jones industrial index (DJX). In Table 3 we summarize the results for the median estimator (estimator 2 in equation 10).[9] We find highly comparable results to those of the SPX: the implied interest rate is on average higher than the government bond yield by about 40 basis points, which is invariant to maturity.

Given how comparable the results for the DJX are to the SPX we only plot the implied continuously compounded interest rate the 1-year maturity as an illustration in Figure XVI. The graphs exhibit very much the same pattern, though the implied rates are somewhat noisier than the ones implied by the SPX. Next we repeat the efficiency analysis of Figure IX but now for DJX. The results are summarized in Figure XVII where we plot the standard error of the OLS estimate of equation 2. The results are comparable to the SPX though the average level of efficiency is substantially lower, with an average standard error of the minutely level estimated rate equal to 3.4 basis points, and spikes that occasionally go as high as 38 basis points. Because our daily estimates are computed by taking a median over all the minute-level observations, those estimates will of course have much smaller standard errors.

Finally, we study how the interest rates implied by the DJX differ from those implied by the SPX. For each maturity, we compute a difference between the DJX and the SPX rate

[9] The regression-based estimator gives highly comparable results.

Table 3
Summary Statistics of DJX Option Implied Interest Rates 2004-2018

Zero Coupon Yields: 6 month maturity			
	Mean	St. Dev.	AR(1) (daily)
Option Implied DJX	0.0184	0.0171	0.9906
Government Bond	0.0144	0.0166	0.9998
Option Implied DJX - Government Bond	0.0040	0.0029	0.6756

Zero Coupon Yields: 12 month maturity			
	Mean	St. Dev.	AR(1) (daily)
Option Implied DJX	0.0190	0.0168	0.9961
Government Bond	0.0150	0.0163	0.9997
Option Implied DJX - Government Bond	0.0040	0.0023	0.7787

Zero Coupon Yields: 18 month maturity			
	Mean	St. Dev.	AR(1) (daily)
Option Implied DJX	0.0197	0.0164	0.9982
Government Bond	0.0159	0.0158	0.9996
Option Implied DJX - Government Bond	0.0039	0.0021	0.8875

and we report the characteristics of that series in table 4.

Table 4
Difference between DJX and SPX Option Implied Interest Rates 2004-2018

Maturity	6-month	12-month	18-month
Mean	0.00046	0.00023	0.00021
Stdev	0.00224	0.00121	0.00103
AR(1) (daily)	0.4302	0.49587	0.5710

The table shows that while on average the rates are very close, substantial persistent daily deviations occur. As an illustration, Figure XVIII plots the differences between the two yields for the 12 month maturity.

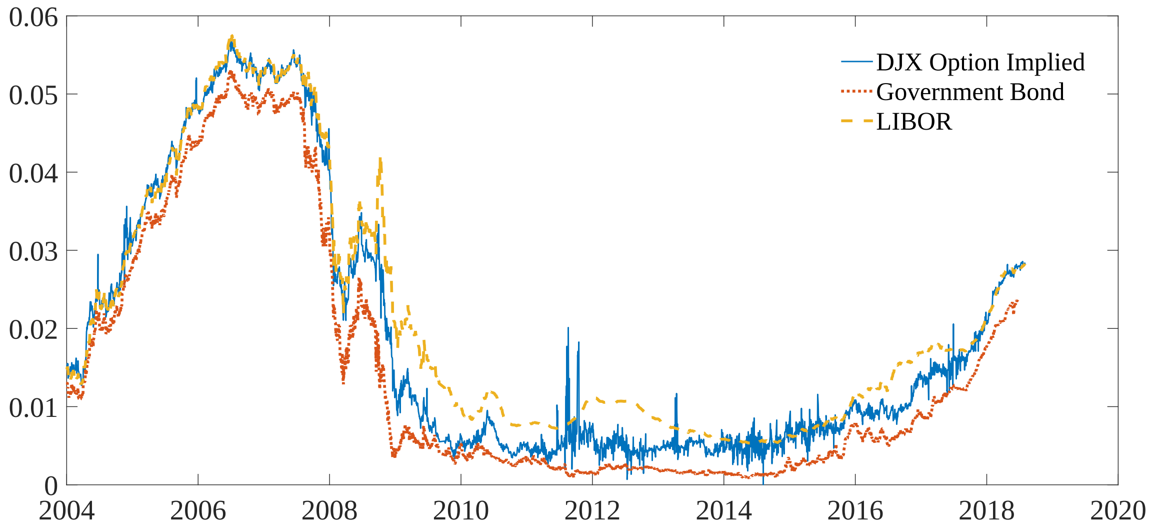


FIGURE XVI
Comparison of 1-year zero coupon interest rates implied from DJX options with government bond rates and LIBOR rates. All rates are continuously compounded.

6.1.3. Rates from Commodity Markets

To construct a risk free asset in commodity markets we use the cost-of-carry relationship between the futures price ($F_{t,T}$ and the spot price S_t) which states that:

$$F_{t,T} = S_t \exp\left((r_{t,T} + c_{t,T})T\right). \tag{23}$$

where $r_{t,T}$ is the implied continuously compounded risk free interest rate and $c_{t,T}$ is the net storage cost of the commodity. To derive estimates of the risk free interest rate, we focus on futures contracts on underlying assets that are very cheap to store relative to their underlying value, implying that the term $c_{t,T}$ is essentially zero. As such we focus on precious metals: gold, silver and platinum. The risk-free rate is then computed as:

$$r_{t,T} = \frac{1}{T}\ln\left(\frac{F_t}{S_t}\right). \tag{24}$$

Our data set contains all futures trades made between May 2007 and January 2018 on the Chicago Mercantile Exchange (CME) regarding three precious metals: gold, silver and

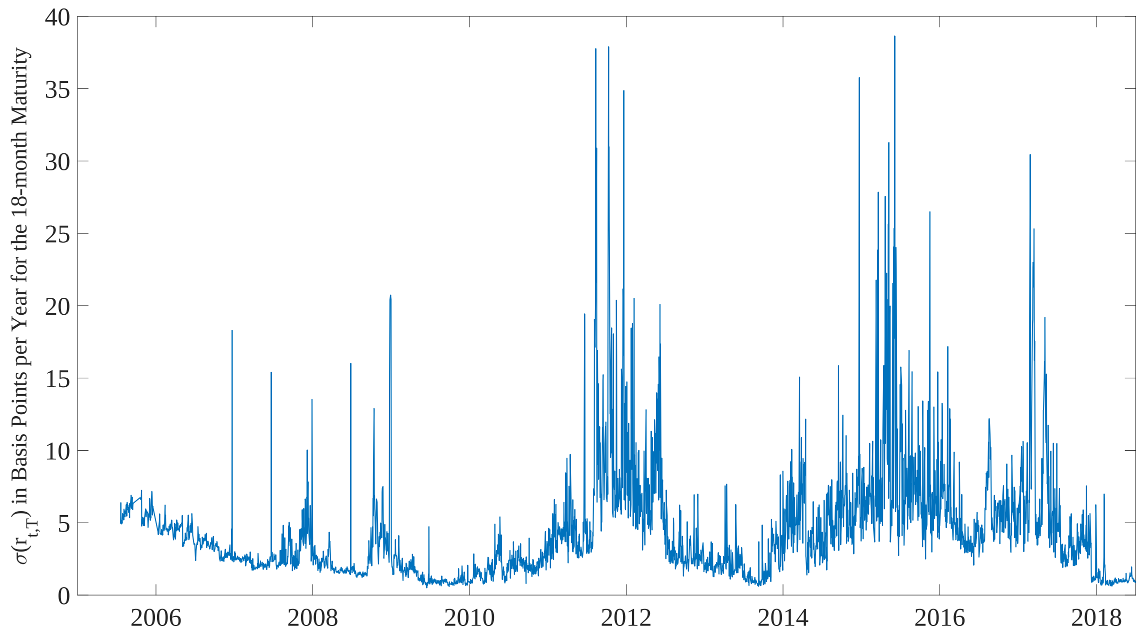


FIGURE XVII

Efficiency in the DJX option market expressed as the standard error around the implied risk-free rate.

platinum. Unlike the CBOE data, which also contains quotes, the database we purchased only contains trades.

In Table 5 we summarize the key statistics for gold and silver implied interest rates. We compare these rates to the government bond yields as implied by the NSS parameters (Gürkaynak et al. (2007)). The table shows that the estimated convenience yield for government bonds relative to metal-implied interest rates is the same as for our previous estimates and equal to about 40 basis points for gold with no apparent relation to maturity. For silver the order of magnitude is the same, but there now seems to be a maturity dependence of the estimate, with the convenience yield decreasing with maturity. For platinum, the data is not sufficiently rich to obtain (interpolated) term structure data. However, the average convenience yield across all available maturities is 50 basis points. The volatility of the daily estimates is large, partly due to the fact that we only have trade data and not quote data.

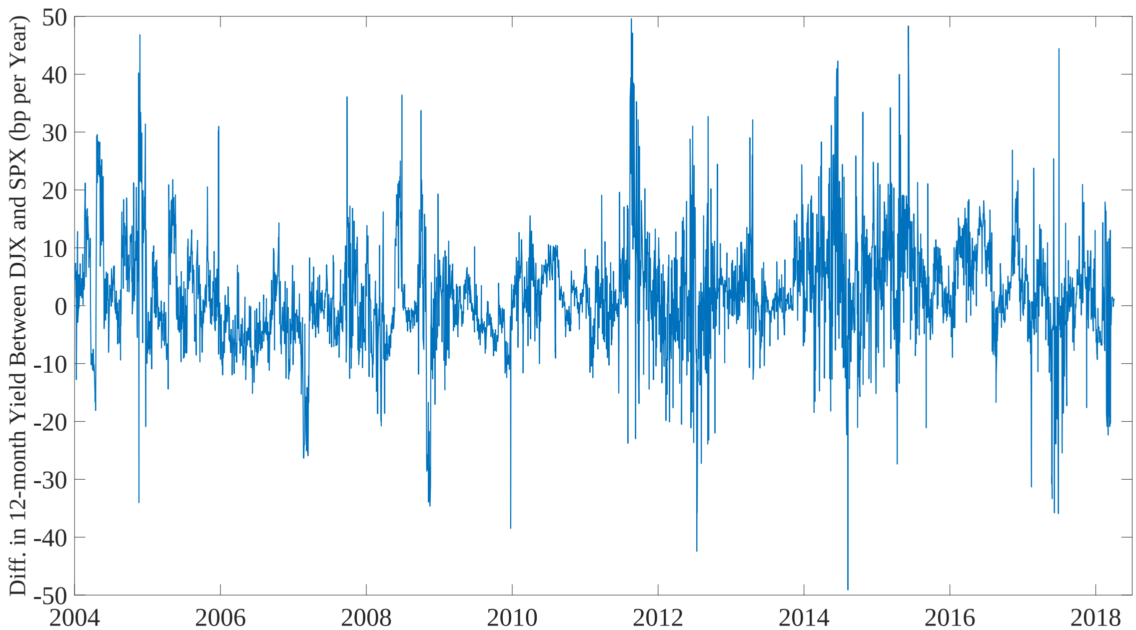


FIGURE XVIII
Difference in Daily Continuously Compounded Implied 12-month Zero Coupon Yield Between the DJX and the SPX in Basis Points per Year.

Table 5
Risk-free rates and convenience yields implied by precious metal prices

Zero Coupon Yield Curve	Gold		Silver	
	Mean	St. Dev	Mean	St. Dev
Metal implied 6m	0.0118	0.0123	0.0133	0.0174
Metal implied 12m	0.0120	0.0117	0.0116	0.0126
Metal implied 18m	0.0127	0.0112	0.0116	0.0124
Metal Implied - Gov. Bond 6m	0.0043	0.0035	0.0054	0.0117
Metal Implied - Gov. Bond 12m	0.0040	0.0027	0.0036	0.0049
Metal Implied - Gov. Bond 18m	0.0037	0.0027	0.0024	0.0050

6.2. Bid Ask Spreads and Other Microstructure Measures

One potential concern with our estimates of the time value of money is that frictions distinct from the convenience yield on safe assets could bias our implied interest rates. For example, it is possible that our option-implied interest rates are systematically above or below true measures of the time value of money when the option market is particularly illiquid. While our SPX options do seem to be extremely liquid and imply an extremely precise rate estimate, we aim to show in this section that option market illiquidity would not cause us to overestimate or underestimate the time value of money. To compute our implied interest rates, we have followed the common practice of using midpoints of bids and asks (similar to the computation of the VIX index by the CBOE). If bid-ask spreads are symmetric around a true measure of an option's value, then an expanding bid ask spread would not change the value of the midpoint. However, if bid ask spreads expand and contract asymmetrically, they could induce bias in an option's midpoint value. In this section, we explore this issue, and document that for our benchmark estimates (using S&P500 index options) observable measures of frictions (such as bid-ask spreads and market efficiency measures) in the option market do not seem related to our estimated rates. A first indication that such frictions are not influencing the level of our rates is that on average the DJX option market is substantially less liquid then the SPX option market, yet produces the same average level of interest rates. Furthermore, and as argued before, we find similar convenience yields using the futures market for precious metals, suggesting that the only frictions of concern must be common across several markets.

To further analyze the issues raised above, we compute a daily bid-ask spread measure, as well as a daily measure of option market efficiency using the cross-sectional R-squared measure of estimator 1 (see equation 2). For each minute, each maturity, and each strike, we compute the bid ask spread by taking the difference between the bid and the ask and dividing it by the mid price. We then construct a daily measure by taking the median over all those bid-ask spreads within the day. We do this separately for puts and calls, so that we can evaluate the influence of each option type separately in the regression (variables bid-ask-all-calls and bid-ask-all-puts). Secondly, to make sure that the variation in our bid-ask spread measure is not driven by the level of the option prices (i.e. the denominator of our bid-ask spread measure) we repeat the procedure above, but now using only options that are less then 10% away from the current index level. That is, if the index level is 2000, we only look at strike prices between 1800 and 2200 (variables bid-ask-atm-calls and bid-ask-atm-puts). We also construct the measure for the complement of that set: only using options with strikes outside of that 10% band (variables bid-ask-otm-calls and bid-ask-otmputs). Finally, to construct the daily option market efficiency measure, we simply take the daily median over the R-squared of our regression, using maturities close to 1 year (and interpolate to get an exact 1-year fit). Because all the values are so close to 1 (the typical value is 0.9999998) we take the natural logarithm and multiply by 1,000,000. This leads to a series with a standard deviation of 0.2. Because the efficiency measure features 5 large outliers, we also run the analysis with those 5 outliers excluded.

To see if our bid-ask spread and market efficiency measures predict distortions in our estimate of the time value of money, we need to compare our Box rates to some other rates that accurately measure the time value of money. The spread between these two rates should be strongly predictable by our bid-ask spread and market efficiency measures if microstructure frictions are distorting our Box rate measure of the time value of money. In the period before 2007, when our rate is almost identical to LIBOR and banks were not thought to be risky borrowers, the Box-LIBOR spread is an ideal measure of the accuracy of our rate. After 2007, this spread is driven primarily by the credit risk of banks and is no longer an accurate proxy for the distortions we wish to measure. We therefore run regressions of the Box-LIBOR spread on our bid-ask spread and market efficiency measures from 2004 to 2006 to test the hypothesis that option microstructure frictions can bias our Box rate estimates away from the time value of money.

We summarize our results in Table 6. The left-hand side of the regression is the daily Box-LIBOR spread between January 1st 2004 and December 31st 2006, i.e. 755 daily observations, which we regress on the friction measures mentioned above. The regression results show that the option market frictions have a negligible explanatory power for the spread with low R-squared values. The highest combined R-squared we obtain is 13%. The coefficients on all the log bid ask spread measures indicates that a doubling of bid ask spreads lowers our box rate estimate by a few basis points. The largest coefficient is on the bid-ask spread measure for at-the-money calls, and equals -8bp, suggesting that our convenience yield could be slightly underestimated during periods of high bid-ask spreads for these options. Given that the standard deviation of this log bid ask spread measure for at-the-money calls is about 0.2, a doubling of bid ask spreads implies a 5 standard deviation change.[10] Given that our R-squared measure has almost no predictive power and that put and call bid-ask spreads

[10]The difference between the maximum and the minimum of the variable in the data equals 1.1.

predict the Box-LIBOR spread with opposite signs, it is not even clear whether an overall decrease in option market liquidity predicts an increase or a decrease in the Box-LIBOR spread.

Table 6
Bid Ask Spreads, Efficiency and the Box Rate

	Box-LIBOR spread (12-month maturity)					
Constant	-0.00048	-0.00179	-0.00118	0.00033	-0.00179	-0.00150
log (bid-ask-all-calls)	-0.00029					
t-stat	-3.19					
log (bid-ask-all-puts)	0.00010					
t-stat	1.26					
log (bid-ask-atm-calls)		-0.00084			-0.00084	-0.00080
t-stat		-8.99			-8.99	-8.50
log (bid-ask-atm-puts)		0.00017			0.00017	0.00021
t-stat		2.27			2.26	2.82
log (bid-ask-not-atm-calls)			-0.00043			
t-stat			-3.35			
log (bid-ask-not-atm-puts)			0.00025			
t-stat			3.78			
Efficiency (Cross-sectional R2)				-0.0000002	-0.0000002	
t-stat				-1.46	-1.49	
Efficiency winsorized						0.00023
t-stat						3.29
R-squared	2.3%	11.5%	7.2%	0.20%	11.7%	12.9%
Number of daily obs	755	755	755	755	755	750

6.3. Price Discovery

As a last robustness analysis, we examine the speed of price discovery for box rates and compare it to the speed in treasury markets. In particular, we investigate how fast rates converge to a new stable level that incorporates news in Federal Open Market Committee (FOMC) announcements. Previous research (Fleming and Piazzesi (2005)) has used treasury yield data from GovPX to show that government bond yields respond quickly to such announcements. We demonstrate that the speed of convergence in our minute-level box rate data is as fast, if not faster, than the convergence in treasury yields. The advantage of our box rates is that we have quotes at every minute for all maturities while GovPX is irregularly spaced with frequent gaps. For this reason, to appropriately compare our high-frequency rates with the Treasury security tick data from GovPX, we first select the government bonds with the highest market activity in a given FOMC meeting day. We then match these bonds with the closest box rates in terms of maturity with a maximum difference in maturities of 30 days.

Our price-discovery exercise closely mimics Fleming and Piazzesi (2005). As in Section 3, we derive policy surprises from the prices of fed funds futures traded on the Chicago Board of Trade (CBOT). We compute policy surprises as the difference between the yield implied by the last trade executed at most 10 minutes before the announcement release and the first trade made at least 20 minutes after the announcement. Following Kuttner (2001) and Nakamura and Steinsson (2018) we define the policy surprise to be the innovation in the current-month futures rate scaled up to reflect the number of days left in that month. For announcements made in the last seven days of the month we use the next month's futures contract.

Two interesting and contrasting cases are depicted in Figure A.1 and Figure A.2. On June 9, 2006 the Federal Open Market Committee decided to raise its target for the federal funds rate by 25 basis points. Both box rates and government yields unambiguously dropped. The reason was a negative target rate surprise (estimated as -2 basis points). Consistent with such a surprise, long-term box rates and government yields concurrently dropped by about 3.4 basis points at announcement, as shown by the bottom Panel of Figure A.1. Instead on October 31, 2007 the Federal Reserve decided to cut its key Fed funds rate by 25 bps. In spite of a negative target rate surprise, US Treasuries sold off sharply after the statement, with yields on longer-term notes rising by about 5 bps at announcement and almost 10 bps by the end of the trading session. The market and Fed watchers took the view that the Fed would be reluctant to cut the Fed funds rate again, given the upward pressure on inflation from crude oil and commodity prices. That this was the consensus can be seen from the simultaneous surge of both long-term box rates and government bond yields in the top Panel of Figure A.2.

Beyond the individual cases, a more comprehensive analysis is necessary to assess the speed of response of our rate to FOMC announcements. We compute changes in both rates in 5-minute intervals around the announcement release. Figure XIX reports the average 5-minute absolute yield changes (volatility) for all matched securities and all FOMC announcement days. Both Treasury yields and box rates appear to adjust immediately at the time of announcement. Furthermore, a slightly higher volatility seems to persist in the hours after the announcement. These volatility patterns around announcement provide evidence that both rates respond with similar speeds to news.

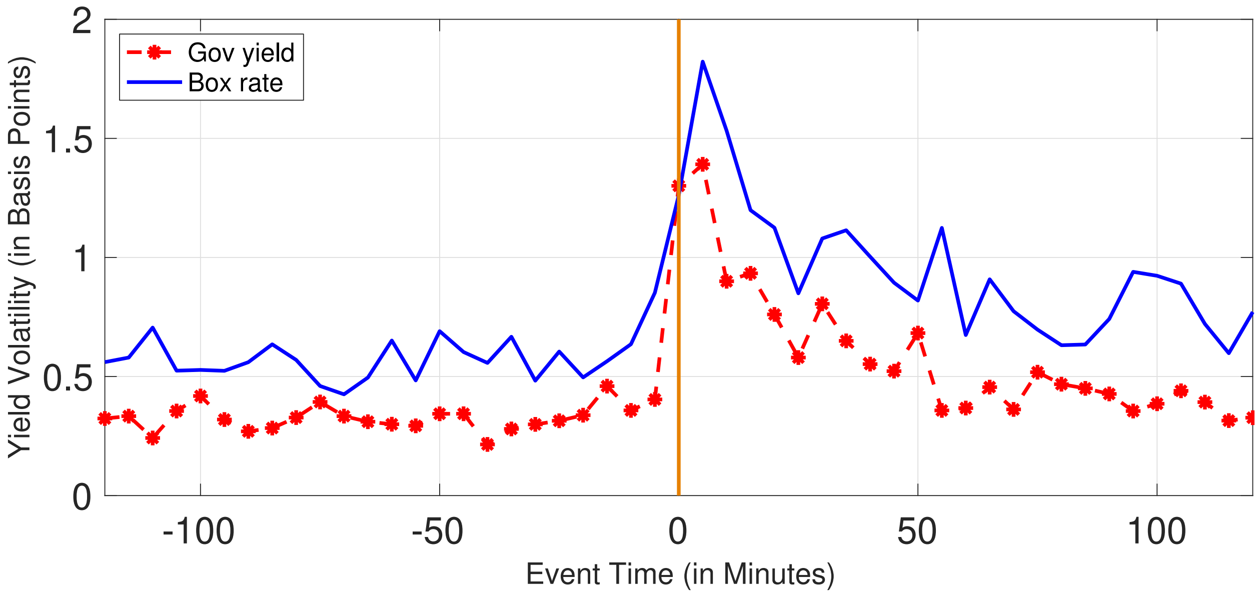
To calculate the speed of convergence, we then proceed by regressing rate changes over various time intervals around announcement on the fed funds target rate surprises. For both the government and the box rates, the largest responses occur in the interval including the announcement release. However, unlike the box rate, the government bond yields exhibit a sluggish response to target rate surprises consistent with the evidence documented by Fleming and Piazzesi (2005). The regression estimates yield additional support for the usage of the box rate when evaluating the market behavior at high-frequency.

Table 7
Effects of Fed funds rate surprises on yields around FOMC announcements

	Interval of Analysis				
Security	$(-45, -25)$	$(-25, -5)$	$(-5, 25)$	$(25, 55)$	$(55, 80)$
Box rate	0.034	-0.019	1.189***	0.364***	0.067
	(0.069)	(0.080)	(0.197)	(0.101)	(0.082)
Government	0.011	-0.016	0.463**	0.179*	0.165***
	(0.041)	(0.035)	(0.210)	(0.099)	(0.055)

Notes: The table shows the results from regressing the innovations in box rates or government bond yields on fed funds rate surprises for various intervals around the announcement release. Fed funds surprise is the variation in the current-month futures rate from the last trade executed at most 10 minutes before the announcement to the first trade made at least 20 minutes after the announcement.

FIGURE XIX
Yield volatility on FOMC announcements



The figure shows the average absolute rate changes around FOMC announcement releases.

7. Other Arbitrage Measures

In this section, we replicate several bond arbitrage measures from the literature and compare them to the dynamics of our estimated convenience yield. We consider four distinct categories of arbitrage spreads using government bond data. Two of them relate to zero coupon bond arbitrages, which can be computed without estimating (and interpolating) a yield curve, and two of them involve bonds with coupon payments that do require an estimated yield curve.

7.1. Zero Coupon Bond Arbitrages

6 month Spread

First, we consider the spread between notes/bonds that mature within the next 6 months and yields on treasury bills that mature on the exact same date. Treasury bills are more liquid and therefore tend to have lower yields (Amihud and Mendelson (1991)). Because treasury securities pay coupons every 6 months, there are no intermediate coupon payments for either security used in constructing this spread. For each day, we compute the median of the continuously compounded yields to construct a daily time series.

STRIP Spread

Second, we consider the spread between two types of STRIPS (Separate Trading of Registered Interest and Principal of Securities) constructed respectively from interest and principal payments on U.S. government debt. These securities pay identical cash flows and are backed by the full faith of the U.S. government, so any difference between the yields on coupon vs principal STRIPS identifies an arbitrage. In general, whichever of the principal or interest STRIP that has a higher supply outstanding tends to have a lower yield. At short maturities, interest STRIPS are in larger supply while at long maturities principal STRIPS are.[11] Because all principal and interest payments happen on a regular 6-month schedule, there are enough overlapping bonds to consider only spreads between interest and principal strips that mature on exactly the same day. We present averages of both the level as well as the value of this spread across all maturity matched pairs of coupon and principal STRIPS below.

7.2. Coupon Bond Arbitrages

Because the two spreads we study in the previous section are between pairs of zero coupon securities with the exact same maturity, no assumptions were required regarding the shape of the yield curve to construct them. This is not true for the two arbitrage spreads that we consider next. The reason is that these next two measures relate to government bonds that make coupon payments for which no exact matching security may exist. As a result, we compute these spreads by comparing a bond's true yield to the yield implied by fitting a yield curve to all treasury bonds. To estimate this yield curve, we estimate a parametric model following Svensson (1994), and Gürkaynak et al. (2007). A Nelson-Siegel-Svensson (NSS) instantaneous forward rate τ periods in the future is assumed to have the functional form

$$f(\tau) = \beta_0 + \left(\beta_1 + \beta_2 \frac{\tau}{\tau_1}\right) \exp\left(-\frac{\tau}{\tau_1}\right) + \beta_3 \frac{\tau}{\tau_2} \exp\left(-\frac{\tau}{\tau_2}\right).$$

[11] The reason is that all bonds of all maturities pay coupon payments every 6 months and contribute to the coupon-related supply.

Given parameters $(\beta_0, \beta_1, \beta_2, \tau_1, \tau_2)$, this forward rate function uniquely implies a zero coupon yield curve that can be used to price any risk free bond. To estimate the parameters, we use data from GovPX between 3pm and 4pm of each day and consider the price of all off-the-run notes and bonds. Let y_i be the yield to maturity of bond i, D_i be the duration of bond i, and $y_i(\beta_0, \beta_1, \beta_2, \tau_1, \tau_2)$ be its yield to maturity implied by the NSS yield curve. We estimate the parameters of the yield curve for each day by minimizing

$$\sum_i \frac{1}{D_i} \left(y_i - y_i(\beta_0, \beta_1, \beta_2, \tau_1, \tau_2)\right)^2$$

where the sum i goes over all bond quotes between 3 and 4pm that day.

On the Run Spread

We use the NSS yield curve to compute an implied yield for the most recently issued bond of each maturity, called the on-the-run bond, and take its difference from the true yield on that bond. On-the-run bonds tend to be more liquid than off-the-run bonds and therefore trade at a lower yield as shown below. The spread between on- and off-the-run bonds is related to the timing of the treasury auction cycle. This is particularly true for the yield on the on-the-run 10-year bond. We plot the spread between this on-the-run 10-year bond yield and yield implied by the NSS yield curve in Figure XX.

Notes vs Bonds

We also use the NSS yield curve to consider the relative spread between treasury notes (which by definition have a maturity less than 10 years after issuance) and bonds (which mature more than 10 years after issuance), that have less than 10 years of maturity left, following (Musto et al. (2018)). For each note and bond that mature between 3 and 10 years from the day on which the security is traded, we compute the spread between the security's actual yield to maturity and the yield implied by the estimated NSS yield curve. We then take the median of this spread across all notes, and the median of the spread across all bonds on each day and compute a daily difference between these two medians. As the above authors show, this spread is small in normal times but spikes during the financial crisis.

7.3. Data

As mentioned previously, our U.S. treasury security prices come from the GovPX database, which reports trades and quotes from the inter-dealer market for U.S. treasuries. We use indicative quotes, which provide the most frequent measure of bond prices on GovPX from 3 to 4pm on each day. In addition, we have data from Tradeweb on the prices of STRIPS, which are zero coupon bonds created by separating the principal and interest payments on treasury securities. This database provides quotes 2 times a day, and we restrict ourselves to quotes at 3pm. Whenever using quote data, we take the midpoint of the bid and ask as the price measure.

Table 8
Summary Statistics of Government Bond Arbitrages 2004-2018

	Mean (in bp)	St. Dev.
6 month Spread	6.4388	6.9544
STRIP Spread	3.8696	8.8144
On the Run Spread		
All Bonds	0.4945	1.9194
10 year Bond	2.1587	2.4044
Notes vs Bonds	0.3576	0.9573

7.4. Results

First, we present summary statistics on the four above-mentioned government bond arbitrages in Table 8 and we plot them in Figures XX, XXI and XXII.

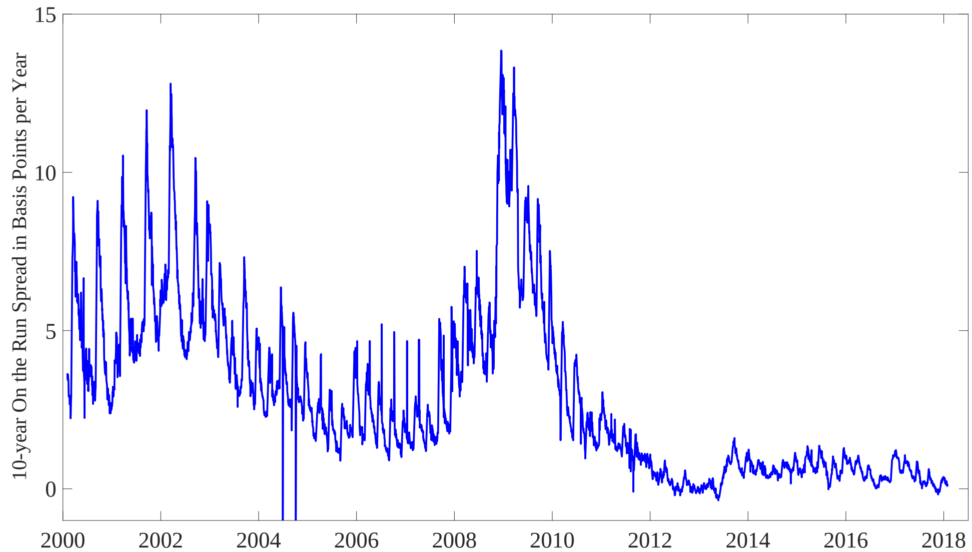


FIGURE XX
Ten Year On-the-Run Spread in Basis Points per Year.

Several patterns appear across all of these arbitrage spreads. First, both their level and volatility generally increase during the financial crisis period of late 2008 and early 2009. Second, most spreads are smallest in the later part of our sample, suggesting that government bond markets are now even more integrated than they were before the crisis. Third, some spreads (such as the 10-year on the run spread) seem to be driven in part by idiosyncratic factors such as the treasury auction cycle. That is, the regular spikes in Figure XX correspond to auction cycle dates.

8. A Multivariate Analysis of Spreads

This section jointly studies the dynamics of our convenience yield measures and the bond spreads computed in the previous section. We document that the SPX option-implied convenience yield measure is exposed to considerably smaller idiosyncratic shocks than all other spreads in the analysis, and that the level of the SPX convenience yield today contains the vast majority of predictive information for its level in the future. This suggests that while

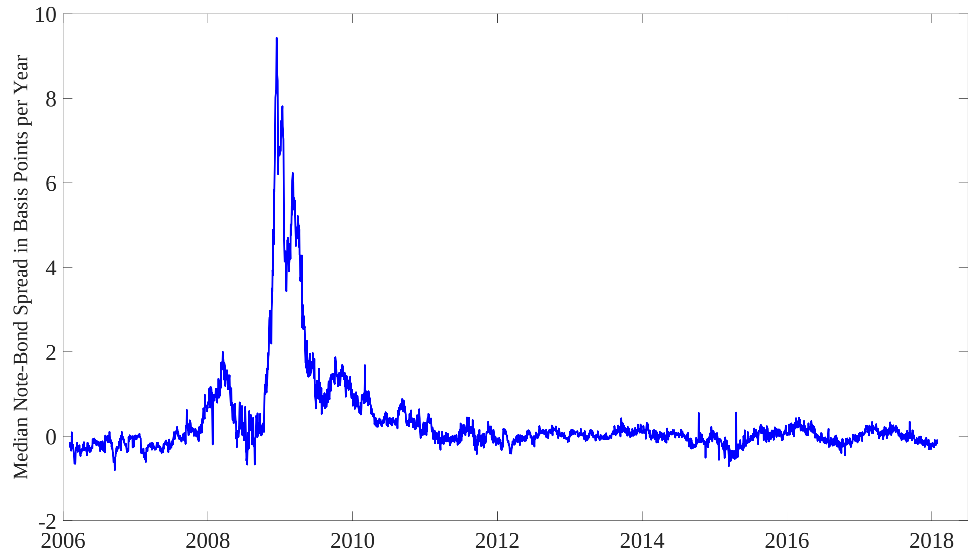


FIGURE XXI
Notes/Bonds Spread in Basis Points per Year.

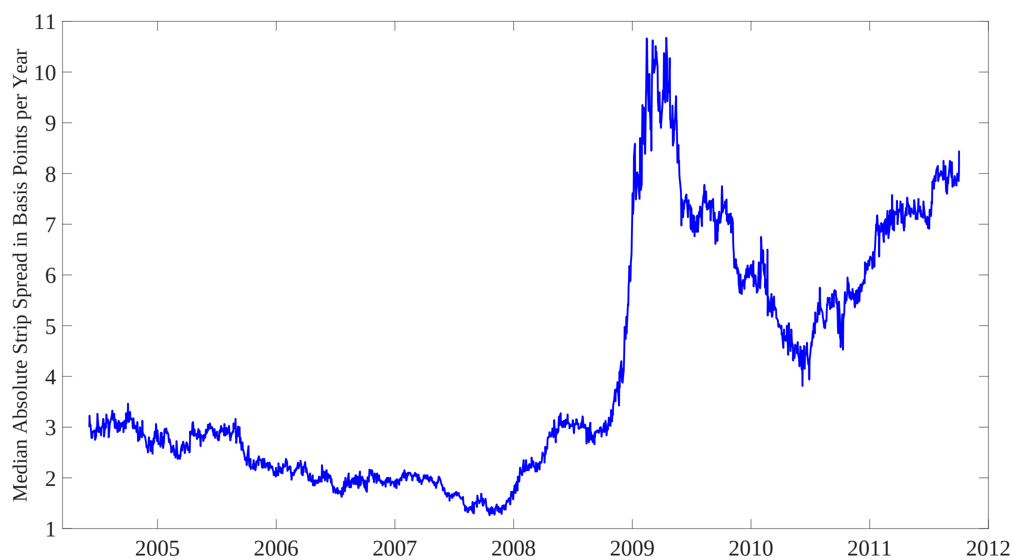


FIGURE XXII
Median Absolute STRIP Spread.

some of the other spreads in our analysis should be thought of as market-specific measures of limits to arbitrage, our convenience yield measure may be thought of as measuring specifically the overall scarcity of safe assets.[12]

To establish these results, we estimate a first order Vector Auto Regression (VAR) on the convenience yields estimated through the SPX, DJX and gold as well as the three government bond spreads from the previous section. The results are reported in Table 9.

Table 9
VAR(1) Analysis of Arbitrage Spreads

	djx	spx	lessthan6	metal	notesbonds	ontherun
djx	0.6798	0.0634	0.0032	-0.0585	0.0001	-0.0002
spx	0.2662	0.9103	-0.0400	0.4142	-0.0002	0.0001
lessthan6	-0.0066	-0.0323	0.5319	1.4711	-0.0018	-0.0015
metal	0.0005	-0.0002	0.0031	0.0223	0.0000	0.0000
notesbonds	1.6658	0.4304	0.2773	4.7072	0.7044	-0.0094
ontherun	0.0671	0.1230	-0.4992	-8.0279	-0.0037	0.4580
constant	2.7326	0.6319	-1.8320	41.4707	0.0078	-0.0281
$R\hat{2}$	0.8332	0.9403	0.3494	0.0126	0.5004	0.2147

The table shows that the option implied series are subject to considerably less idiosyncratic risk than others, while the metal convenience yields are subject to more.[13] As a result, if we are interested in using data on risky asset prices to infer the risk-free rate consistent with the time value of money, the option-implied rates seem to be our best candidate. The R-squareds of predicting the in-sample SPX implied rate is extremely high (94%), and substantially higher than that of the DJX (83%). Government bond arbitrages have intermediate R-squareds, while the metal series have by far the lowest. This implies that there does not seem to be a high degree of unpredictable, non-persistent noise in the SPX implied rates. The SPX-implied rate seems most consistent with the intuitive notion that the time value of money does not have extreme high frequency fluctuations. Another important finding in the vector autoregression is that the option implied rates seem to predict each other, while many series seem to respond to the notes/bonds spread. This seems to be due to the

[12] We thank Eben Lazarus for providing this interpretation of our findings.

[13] This is also due to the fact that the convenience yields on precious metals are estimated with trade data only leading to noisier estimates.

fact that the notes/bond spread spikes dramatically during the U.S. financial crisis but is otherwise very small and that the Box rates are responsive to both the U.S. and European financial crises. The other series we consider seem to have more idiosyncratic variation in their spreads, suggesting that these markets may be relatively more segmented from overall financial conditions.

9. Conclusion

We have constructed and analyzed a novel panel of risk free interest rates that are free of the convenience yield on safe assets. We have presented three important applications of this novel data set: (1) event studies of the effects of central bank policy, (2) the role of convenience yields in bond return predictability, and (3) the importance of excluding convenience yields when computing deviations from covered interest parity in foreign exchange markets. More generally, we wish to advocate for our rates' widespread use in the empirical asset pricing (and intermediary asset pricing) literature. For example, our data is important for the accurate measurement of risk premia on stocks and credit instruments, as it prevents researchers from inadvertently confusing the convenience yield on safe assets with compensation for risk in the traditional asset pricing sense of the word.

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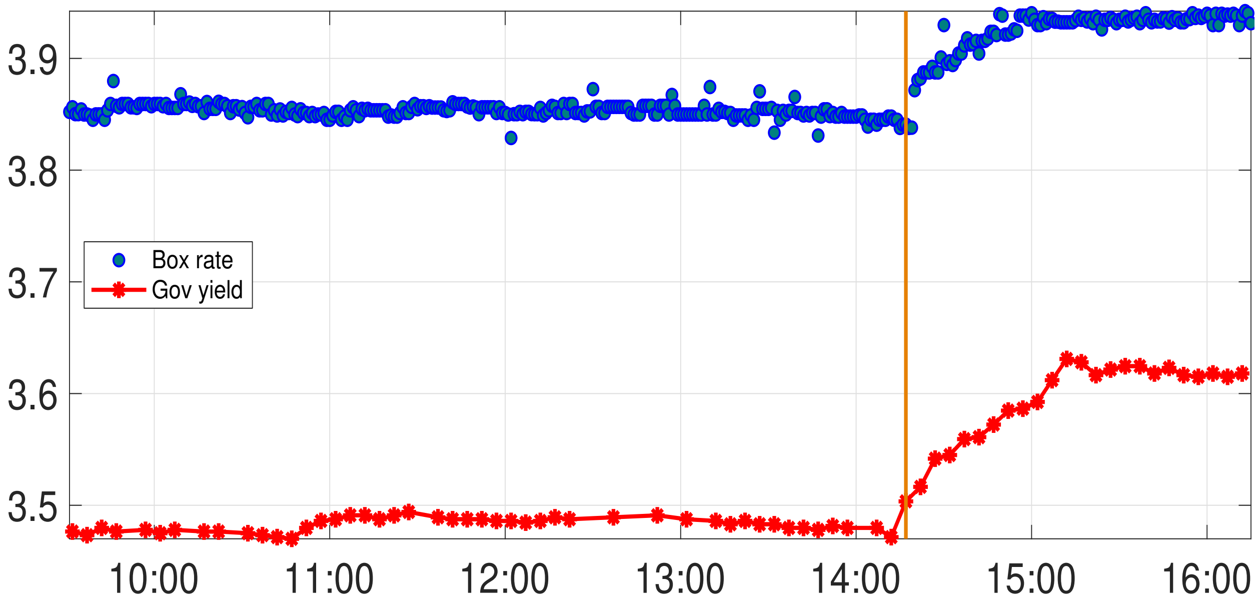
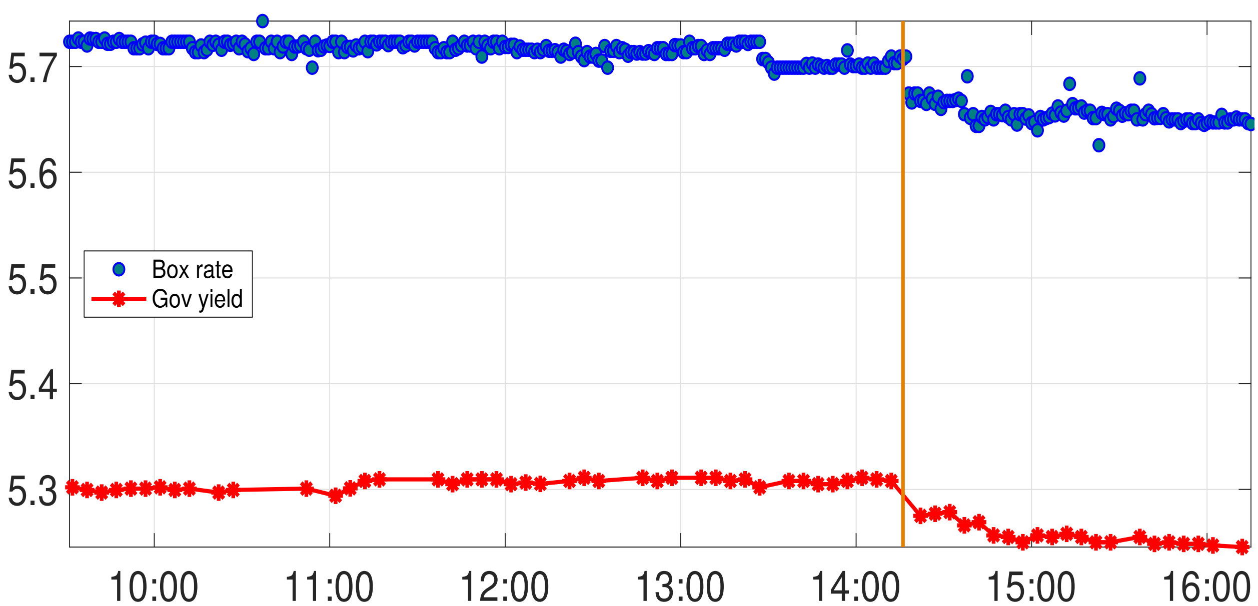
A. Select responses of box rate and government yields to FOMC announcements

FIGURE A.1

Panel A: March 22, 2005



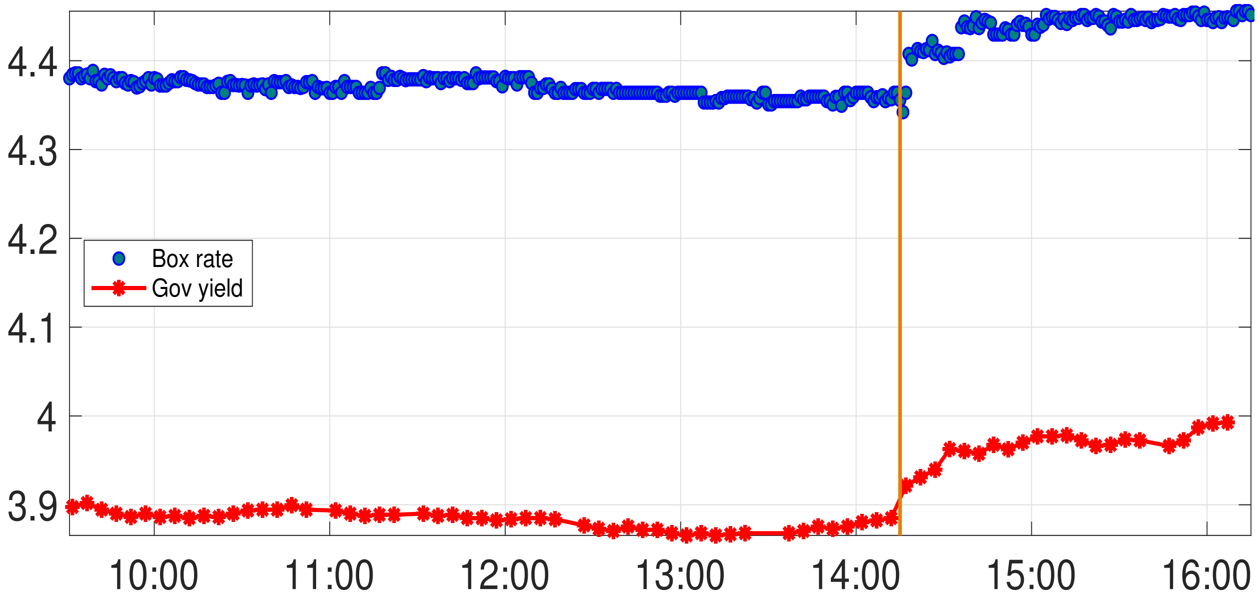
Panel B: June 29, 2006



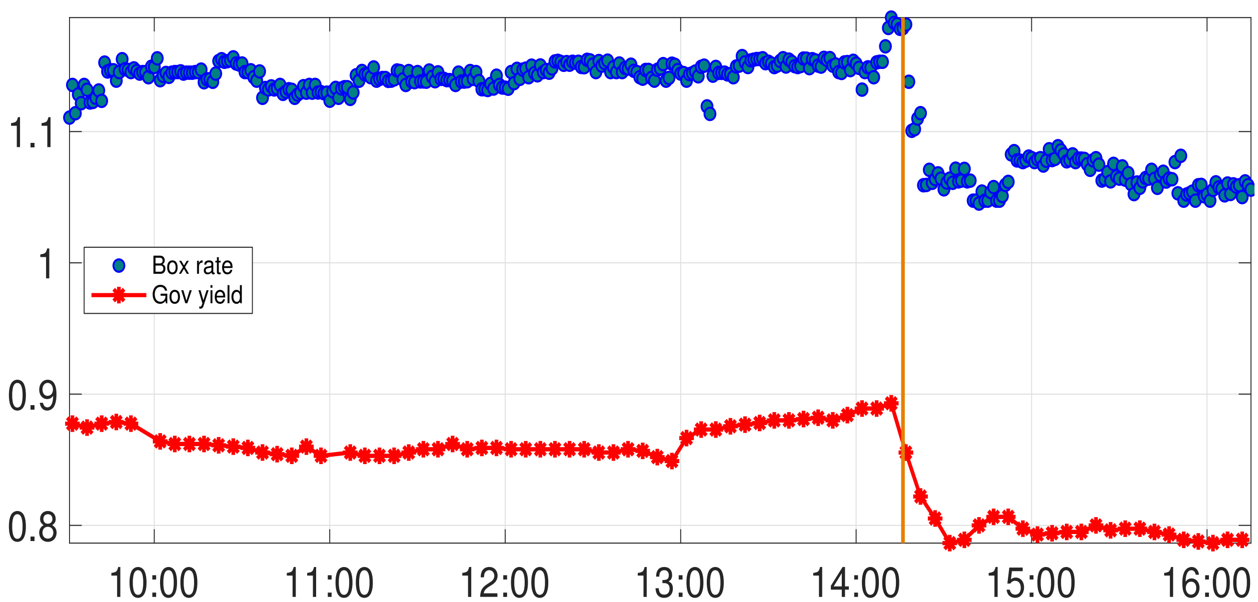
The figure plots the maturity-matched box rates and government yields around the release of the March 22, 2005 and June 29, 2006 FOMC announcements. The maturities are 452 days for Panel A and 541 days for Panel B. The vertical line represents the time of the release.

FIGURE A.2

Panel A: October 31, 2007



Panel B: September 23, 2009



The figure plots the maturity-matched box rates and government yields around the release of the October 31, 2007 and September 23, 2009 FOMC announcements. The maturities are 598 days for Panel A and 633 days for Panel B. The vertical line represents the time of the release.